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16. ABSTRACT

This report was prepared as part of the Ohio River Basin Energy Study (ORBES), a multidisciplinary policy research program supported by the Environmental Protection Agency. The study region consists of all of Kentucky, most of West Virginia, and substantial portions of Illinois, Indiana, Ohio, and Pennsylvania. By 1988, coal-fired electrical generating capacity in the region is expected to total over 100,000 MWe, versus about 11,000 MWe projected for nuclear-fueled capacity by that year. Thus, the ORBES emphasis was on coal-fired generation. This report attempts to fill in some of the gaps in the relative lack of emphasis on the risks and benefits of nuclear electricity production in the study region. It covers the following topics: (1) basic facts about radiation, (2) an overview of the current regulatory framework of the nuclear industry, (3) health risks associated with electricity production by LWRs, (4) the risks of nuclear proliferation, terrorism, and sabotage, (5) comparative economics and healty risks of coal versus nuclear, and (6) the March 1979 accident at Three Mile Island. The reader is urged to consult the references cited for a more complete understanding of the issues.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Energy Conversion Environments	Health Effects Integrated Assessment Conversion Coal Nuclear	

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FOREWORD

The Ohio River Basin Energy Study (ORBES) is an interdisciplinary, multi-university inquiry into the environmental, economic, and social impacts of energy facility development in a major portion of the Ohio River Basin. The study was initiated by the U.S. Environmental Protection Agency in 1976 in response to a directive from the U.S. Senate Appropriations Committee.

Most of the ORBES research was conducted by a group of faculty members at the University of Illinois, Indiana University, the University of Kentucky, the University of Louisville, The Ohio State University, the University of Pittsburgh, Purdue University, and West Virginia University. In a few instances, the necessary expertise was found at other universities or independent research organizations.

This report is one of a series produced in support of the overall ORBES assessment. For a summary of the entire study, see Ohio River Basin Energy Study (ORBES): Main Report, by the ORBES Core Team, also being published by the U.S. Environmental Protection Agency.

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LIST OF ABBREVIATIONS AND ACRONYMS

ACRS	Advisory Committee on Reactor Safeguards
AEC	U.S. Atomic Energy Commission
AFR	Away-from-reactor spent fuel storage basins
BIER	Committee on Biological Effects of Ionizing Radiation
BOM	U.S. Bureau of Mines
BWR	Boiling water reactor
ci	Curie
CONAES	Committee on Nuclear and Alternative Energy Systems
DOE	U.S. Department of Energy
ECCS	Emergency core cooling system
EPA	U.S. Environmental Protection Agency
GESMO	Final Generic Environmental Statement on the Use of Recycle Plutonium Mixed Oxide Fuel in Light Water Cooled Reactors (Nuclear Regulatory Commission Report, August 1976)
GPU	General Public Utilities Service Corporation
HPI	High pressure injection
IAEA	International Atomic Energy Agency
IE	Inspection and Enforcement, NRC Office of
INPO	Institute of Nuclear Power Operations
kw	Kilowatt
KWe	Kilowatt(s) electric

LOCA	Loss-of-coolant accident
LPI	Low pressure injection
LWR	Light water reactor
MT	Metric ton(s)
MTHM	Metric tons heavy metal
MWD	Megawatt days
MWd(t)	Megawatt day(s) (thermal)
MWe	Megawatt(s) electric = 1,000 KWe
MWt	Megawatts thermal
NEIL	Nuclear Flectric Insurance Limited
NPT	Nuclear Non-Proliferation Treaty
NRC	U.S. Nuclear Regulatory Commission
NSAC	Nuclear Safety Analysis Center
NWTS	National Waste Terminal Storage
ORBES	Ohio River Basin Energy Study
OSHA	Occupational Safety and Health Administration
PORV	Pilot-operated relief valve
psi	Pounds per square inch
PWR	Pressurized water reactor
rad	Radiation absorbed dose
SRG	Special Review Group within IE
TMI	Three Mile Island
WIPP	Waste Isolation Pilot Project

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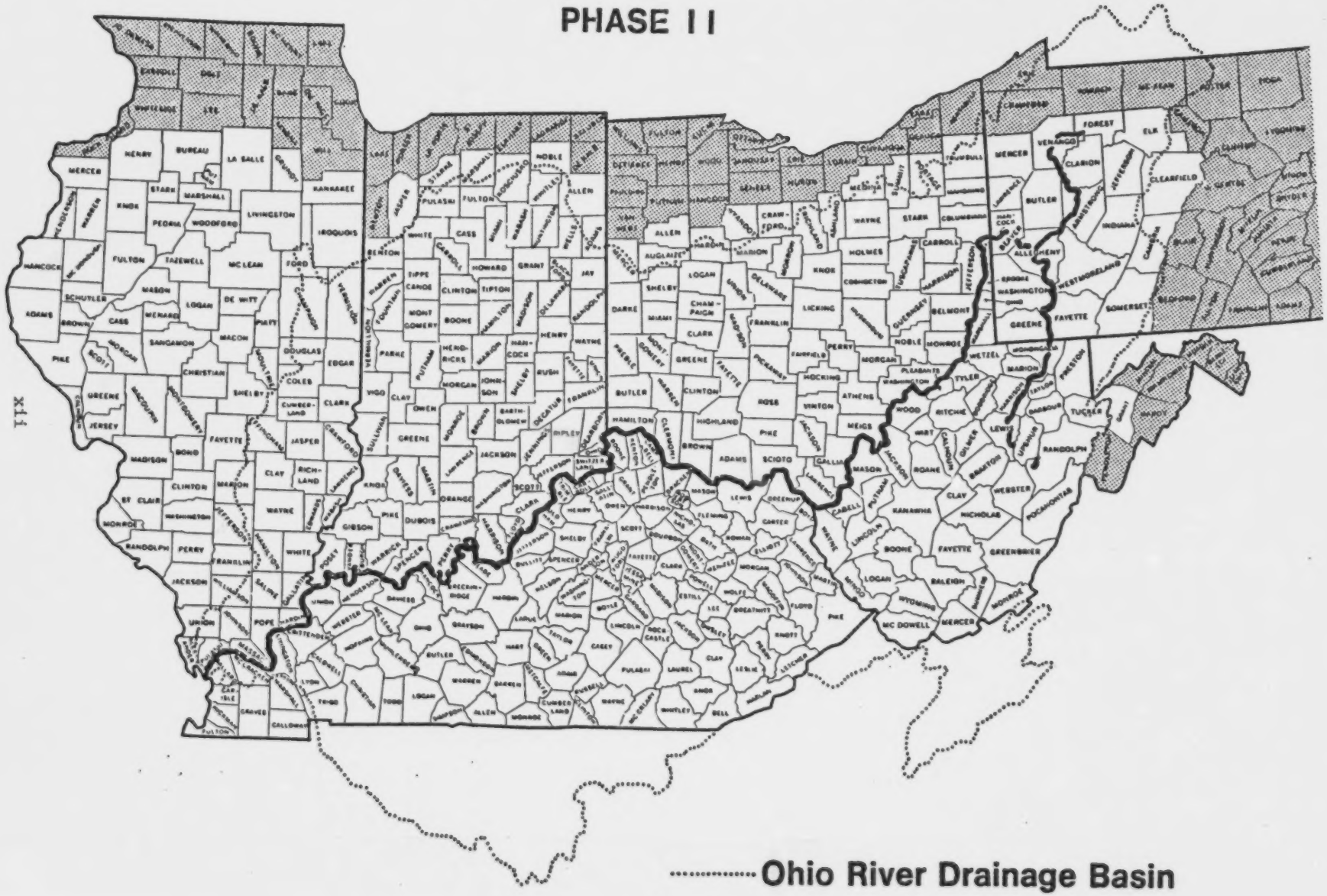
OHIO RIVER BASIN ENERGY STUDY REGION

PHASE II



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CHAPTER 1

INTRODUCTION

BACKGROUND AND SCOPE

The Ohio River Basin Energy Study (ORBES) Phase II region currently has a modest commitment to nuclear electricity generation of somewhat less than 3000 MWe. If present expansion plans come about as scheduled, this commitment will grow to nearly 11,000 MWe by 1988. The region's coal-fired electrical generating capacity is planned to grow from about 75,000 MWe now to over 100,000 MWe in that time frame. ORBES was set up to study the full range of impacts from these and other electricity generating sources which may come on-line by the year 2000. This particular report was commissioned to fill the perceived lack of emphasis on the risks and benefits of nuclear electricity production in the ORBES Phase II main assessment.

Few would doubt that electricity has contributed to the overall well-being of the residents of the area. Reasonably priced electricity has certainly contributed to the economic vitality and high living standard characteristic of the region. But since the general public is subject to the risks as well as the benefits of electricity production, the citizens and their elected and appointed representatives should have a say in how the electricity is produced. This report has attempted to bring together some of the current information on the important nuclear-related issues bearing on this choice.

Traditionally, electric utilities have sought to provide the cheapest possible reliable electric service. Utilities prefer a mix of fuel sources to reduce their overall susceptibility to disruption of reliable service by the loss of any single supply source. For whatever reasons, the figures for expansion plans given above indicate that the ORBES region utilities are moving in the direction of increased reliance on nuclear-fueled generation. At the same time, the public, by its own direct actions and through its elected officials, has expressed increased concern for safer and more environmentally acceptable means of generating electricity.

At least for the near-term future, coal-fired and nuclear-powered generation are the only reasonable alternatives for baseload electricity production. In order to provide a context in which to interpret the relative risks and benefits of nuclear to its alternatives, certain comparable risks and benefits from coal-fired generation have been included. A

comprehensive treatment of coal-related issues has not been presented here since that can be found in other ORBES documents. In fact, many of the environmental effects of nuclear technology, such as land use and thermal effects, are not explored for the same reason. In this report there has been no attempt to resolve the issues raised. The emphasis is rather to draw together some of the data from the literature on which informed decisions may be based.

The report draws heavily upon the results of other summary and synthesis efforts by groups with far greater time and money resources than those involved in the present effort. The references cited should not be neglected by those interested in a more complete understanding of the issues raised here.

REPORT ORGANIZATION

The report begins with a presentation of some of the basics of radiation necessary for the understanding of material in the remainder of the report. Types and sources of radiation are discussed along with definitions of essential terms. Some controversial issues are raised in the section which introduces the subject of radiation health effects.

Chapter 3 gives a broad overview of the regulatory framework under which the nuclear industry currently functions. The roles of the various regulatory agencies with regulatory responsibility are outlined. Current radiation protection standards are presented in some cases and referenced in others.

The health risks associated with the production of electricity by the current generation of light water reactors (LWRs) are treated in Chapter 4. These risks are organized by the stage in the nuclear fuel cycle in which they occur. Aspects of the nuclear fuel cycle which occur at specific geographic locations are shown in Figure 1.1. Additional aspects of the fuel cycle, such as transportation and decommissioning, do not appear in the figure but are treated in separate sections. Background material on each stage in the cycle is presented first. This material includes a description of the processes involved at each stage along with an introduction to some of the major policy issues involved. Next, the risks at each fuel cycle stage are described. Where possible, risks are subdivided into those affecting workers and those affecting the general population. Radiological risks are generally treated separately from other hazards. Risks are further divided into those from normal operation and those from accidents, where appropriate.

Chapter 5 provides a brief introduction to the risks of proliferation, terrorism and sabotage. Horizontal proliferation is treated first, followed by a section which combines a discussion of the risks of terrorism and sabotage.

The authors believe Chapter 6 to be extremely important because it not only summarizes the risks of the nuclear fuel cycle but also provides a context for the rational evaluation of these risks. The context is

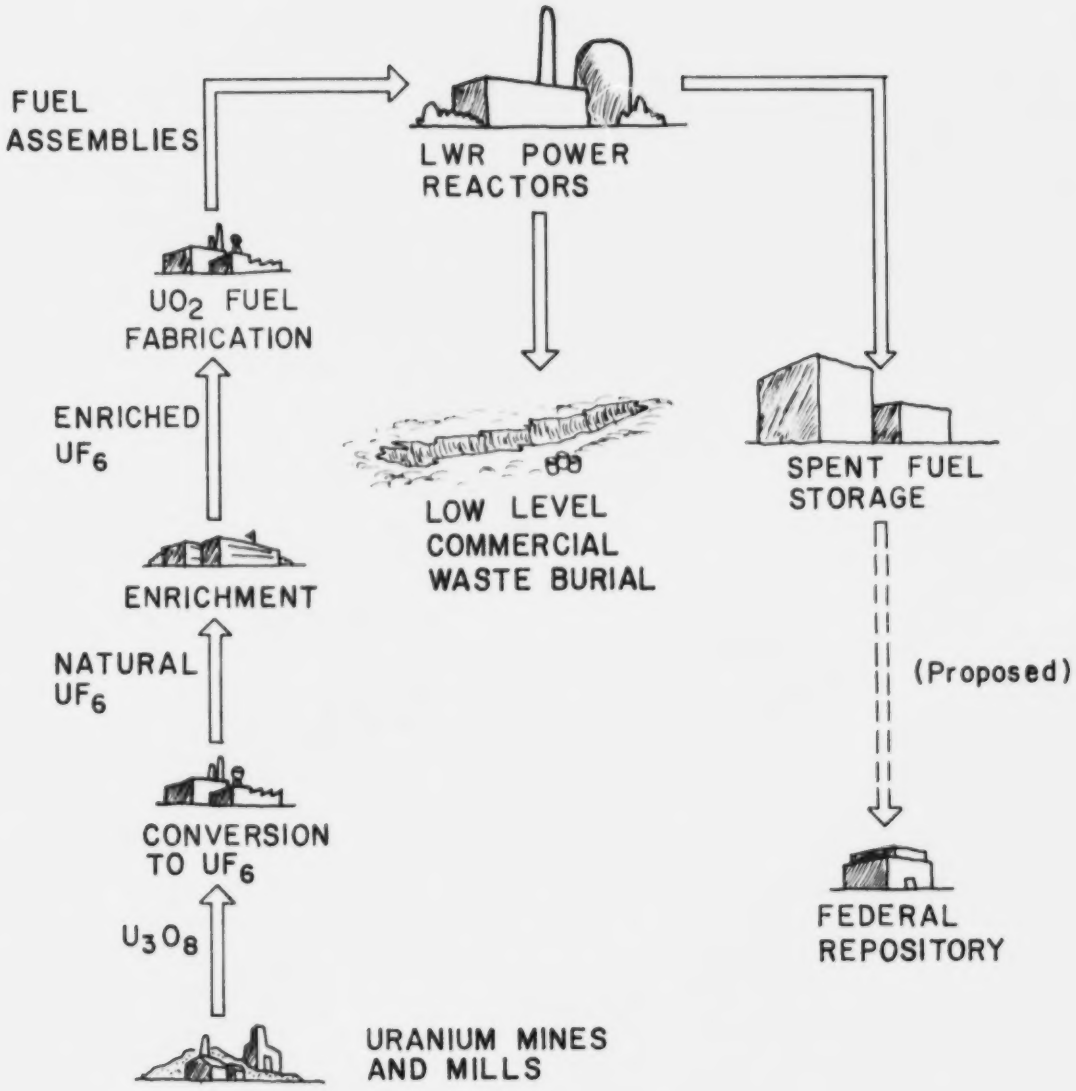


FIG. 1.1 - The Light Water Nuclear Fuel Cycle Without Reprocessing

SOURCE: Modified from Godbee et al., 1978, p. 4

constructed around a comparison with the only reasonable near-term alternative for the production of electricity, namely coal. The economic costs of nuclear-powered and coal-fired electrical generation are compared first. This is followed by a section on the comparative health impacts of the two technologies. Certain other less-quantifiable risks are also introduced.

No report on nuclear energy written at this time would be complete without the inclusion of a discussion of the March 1979 accident at Three Mile Island Unit 2. This has been done in Chapter 7. First, some fundamentals of nuclear reactor operation specific to the Three Mile Island situation are given. This is followed by an account of the accident and the plans for cleanup. The next section deals with the responses of various groups to the accident. An introduction to the literature and a summary of the responses of the Carter Administration, the Nuclear Regulatory Commission, the nuclear industry and the public have been included.

The concluding chapter furnishes an overview of the preceeding material. The major health risks of the nuclear fuel cycle are reviewed along with the highlights of the comparison with coal-fired electrical generation. Additionally, potential implications of the Three Mile Island accident and other considerations affecting the future of nuclear power in this country are summarized.

CHAPTER 2

RADIATION

INTRODUCTION

The intent of this chapter is to provide the fundamental background information on radiation necessary for the understanding of material in subsequent chapters. Many of the terms and concepts used throughout this report are unfamiliar to those for whom this report is intended. Rather than bury this information in an appendix, as is usually the case, it has been placed here so that it is not easily overlooked. Those readers already possessing a working knowledge of radiation need pay no attention to this chapter.

TYPES OF RADIATION

Radiation can be divided into two major types, nonionizing and ionizing. Nonionizing radiation is more familiar to most people because it is integrated into our lives in many important ways. Such common radiation as light, sound waves, microwaves and radio waves fall into the nonionizing category. Although nonionizing radiation can damage living tissue, this type of radiation is not of major concern as a product of the nuclear fuel cycle and will not be discussed further here.

Ionizing radiation is generated by a host of natural and man-made materials (see the section below on sources). The term "ionizing" refers to the process by which a neutral atom loses or gains electrons, thereby acquiring a net charge and becoming an ion. "Ionizing radiation" then refers to particles or photons that have sufficient energy to produce ionization in their passage through a substance or particles that are capable of nuclear interactions in which sufficient energy is released to produce ionization. Forms of ionizing radiation of biological significance include: alpha (α) particles; beta (β) particles; gamma (γ) radiation; and neutrons. The Nuclear Energy Policy Study Group (1977) provides a lucid description of ionizing radiation from which much of the following is taken.

Ionizing radiation is often generated by the inherently unstable nuclei of the atoms of many of the heavier elements. This instability can result in the nuclei emitting ionizing radiation. Alpha particles, just like the nuclei of helium atoms, consist of two neutrons and two protons bound together. Beta particles can be either electrons or positrons

(positively charged particle otherwise identical to the electron). The spontaneous ejection of such particles is known as radioactive decay or disintegration. The immediate product of such decay, aside from the alpha or beta particles, is called a daughter or decay product. The electrical charge on alpha and beta particles causes them to perturb the electron clouds of atoms they encounter, resulting in ionization, ruptured chemical bonds and consequent breakdown of molecules. As beta particles are slowed by transferring their energy through such encounters, some of their initial energy may appear as ordinary X-rays, which are another form of ionizing radiation. Gamma rays are directly emitted by certain radioisotopes in the transition between two energy levels. They are high-energy electromagnetic photons similar to X-rays but with higher energy. Energetic gamma rays are emitted when positive beta particles are stopped and annihilated with electrons. Neutron absorption in a nucleus also produces gamma radiation.

When the nuclei of certain heavy elements split into two parts of comparable mass by the process known as fission, neutrons and other particles are emitted. The fragments of fission are called fission products and the heavy isotopes which undergo fission, such as uranium, plutonium or thorium, are known as fissionable or fissile materials. Neutrons are responsible for the sustained chain reactions which occur in nuclear reactors. Neutron absorption by a nucleus produces a higher isotope which is itself often radioactive. Neutrons are electrically neutral and, therefore, undergo many collisions with nuclei in the process of slowing down. Dense ionization over short distance results from their high-speed collisions with nuclei.

Energy is dissipated along the path of the radiation through a series of collisions with the atoms and nuclei of the material encountered. Molecules along the path are damaged by the breaking of chemical bonds and other chemical changes caused by ionization. High densities of ionization events along the path are roughly equivalent to high intensities of local biological damage. The different forms of radiation described above have different ionization characteristics. Alpha particles and neutrons cause heavy local damage by their high rate of energy transfer. However, alpha particles do not penetrate far. An inch of air or the outside layer of human skin is usually enough to stop alpha particles. Beta particles penetrate tissue to a depth of an inch or so because they lose energy more slowly. Gamma radiation is extremely penetrating.

MEASUREMENT OF IONIZING RADIATION

Radiation absorption by tissue is measured in rad units. One rad is the amount of radiation depositing 100 ergs of energy per gram of tissue. But since alpha particles and neutrons generally cause more biological damage per unit of energy deposited than do beta particles or gamma rays, another unit is introduced to account for the difference. The rem unit accounts for this "quality factor" by enabling all radiation effects to be related to a single measure of dose. The rem is the most common measure used in setting radiation protection standards. One rad of beta or gamma radiation is usually translated into about one rem of biological effec-

tiveness. Neutrons are usually assigned a dose equivalence of 10 rem per rad and alpha particles an equivalence of 20 rem per rad.

Radioactivity is commonly measured in terms of disintegrations per unit time or curies. One curie is equal to 3.7×10^{10} disintegrations per second. Submultiples of radiation and radioactivity are generally expressed in metric units (e.g., 1,000 millirem = 1 rem).

Another widely used description for the rate at which a radioactive substance disintegrates is the radioactive half-life. The disintegration rate depends on the isotopic species under consideration but the process is governed by a definite "decay law." Although it is impossible to tell which individual isotopes in a given quantity of radioactive material will decay within a time interval, the aggregate number of disintegrations in the interval can be specified. The half-life of a material is, as the name implies, the time required for half of the nuclei to decay. Substances range in half-lives from small fractions of a second to billions of years. The neutron, for example, has a half-life of 11.7 minutes while potassium-40 has a half-life of 1.26×10^9 years.

SOURCES OF IONIZING RADIATION

We are all continually impinged upon by radiation from all sides. Some of these sources and their average annual dose rates are shown in Table 2.1. As the table shows, over 60 percent of the average dose is due to natural sources. Cosmic radiation is caused by high-velocity electrons and atomic nuclei from space. Much of this does not reach us at the earth's surface because of the shielding effect of the atmosphere. However, a trip in an airplane or a stay in Denver will expose one to a dose much higher than that given in the table. The trip to Denver would also involve significantly higher exposure from terrestrial radiation due to the type of rocks which underlie the area. A portion of our radiation dose even comes from radioactive constituents within our bodies.

Among the man-made sources of radiation, it can be seen that diagnostic medical X-rays contribute about 90 percent of the average dose. Individuals are, of course, not equally exposed to radiation from any source. The dose rate in 1975 due to all preceding nuclear power generation activities contributed about 0.03 percent of the man-made dose rate and about 0.01 percent to the total from all sources.

Schmidt and Bodansky (1976) put the radiation from normal operation of a nuclear reactor in perspective by stating that "... the incremental radiation received by a person residing continuously 24 hours a day at the fence of a nuclear reactor would not exceed 1/10th of the natural environmental dose. It is less, for example, than the extra dose received if one lives in a brick house, with its radioactive materials, rather than in a wood house " (p. 57).

Current dose rates, like those in Table 2.1, can be misleading if one does not realize that radioactive releases from fuel cycle activities may continue for years after the actual power generation and could gradually

Table 2.1. Estimates of Annual Whole-Body Dose Rates in the U.S.

Source of Radiation	Average Dose Rates (Millirem/year)
Natural	
Environmental	
Cosmic Radiation	45
Terrestrial Radiation	60
Internal Radioactive Isotopes	25
Subtotal	130
Man-Made	
Environmental	
Global Fallout	4
Nuclear Power	0.023
Medical	
Diagnostic	72
Radiopharmaceuticals	1
Occupational	0.8
Miscellaneous	2
Subtotal	80
TOTAL	210

SOURCES: Nuclear Energy Policy Study Group, 1977; Advisory Committee on the Biological Effects of Ionizing Radiation, 1972; and Klement et al., 1972.

build up in the environment and in human tissue. The commitment to future radiation exposure from present power generation activity is often referred to as the dose commitment over a prescribed period of time.

RADIATION AND HUMAN HEALTH

There are two distinct aspects to calculating the radiation dose delivered to the body, external and internal. The external dose is a function of the energies of the radiations involved and their absorption co-efficients in the human body and in external media interposed between source and subject, such as air or water. Additional factors must be considered in order to calculate internal dose from radioactive materials ingested or inhaled into the body. These factors include the migration of certain substances to specific organs, the gradual loss of radioactive materials by excretion, and the shielding of certain tissues from short-range radiation by mucus (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979). External radiation dose is often given as the whole-body dose and the dose to a specific organ may be translated into a whole-body dose equivalent. The dose to a population is usually expressed in person-rem which is the total dose in rem received by the individuals in a given population. In other words, person-rem is the product of the number of people exposed and the total rem exposure.

The dose, as defined above, is dependent on the pathway by which the radiation reaches the body. The Committee on Literature Survey of Risks Associated with Nuclear Power (1979) provides a detailed discussion of these pathways. Some of their findings are given here. Radiation migrates to humans through the atmosphere, through bodies of water, through soil, and through the human food chain. For the most part, these are complex processes requiring elaborate models to predict human exposure.

A great deal of effort has gone into transport modeling at local, regional and global scales to predict human doses from the atmosphere. Atomospheric radiation can be delivered to humans by direct external radiation from the air, by internal radiation through inhalation and by deposition on plants. Deposition on plants can affect man through the food chain by either the direct consumption of irradiated plants or by the ingestion of animals fed on radioactive plants. Leafy crops are the major concern. "Bioaccumulation factors" or "concentration ratios" must be considered when radioactive materials enter the food chain. The concentration of iodine-131 in cow's milk is a prominent example of this pathway.

Transport through the hydrosphere is also of concern. Radioactivity in water bodies tends to be scavenged by sediments and by chemical precipitation, particularly in the oceans, working to reduce human dose. Direct external gamma radiation from water is possible, though thought to be insignificant. More important are ingestion by drinking, and food chain pathways such as eating contaminated fish and consumption of land crops irrigated with contaminated water. Pathways through the soil require transport by water. Ion exchange between soil particles and radioactive

materials tends to retard the movement of the latter. Transport of plutonium through the soil at the Maxey Flats, Kentucky low-level waste disposal site poses an anomalous soil transport question which is not fully understood.

The radiation that eventually reaches man by any of these pathways can produce two broad categories of biological effects: those that result from the killing of cells by radiation; and those that can be produced by a mutation in a single cell, or that involve mutation-like processes (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979). It is generally agreed that for cell death, the curve relating dose to effects or response (dose-response curve) shows a threshold below which the effect does not occur. Effects of this type include acute lethality, neonatal death, certain congenital abnormalities and sterility which are evident at high doses or high dose rates. A dose equivalent of about 300 to 350 rem delivered to all parts of the body equally over a short period of time will result in death in 50 percent of the individuals exposed if medical treatment is not administered. Such deaths would occur several weeks after exposure (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979).

The major concerns at low doses or low dose rates are cancers which may develop in an exposed individual after some latency period, and genetic effects which may show up in the descendants of irradiated persons (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979; and Radford, 1979). A major as yet unresolved controversy surrounds the quantification of health effects due to low-level radiation. The Nationl Academy of Sciences' Committee on Biological Effects of Ionizing Radiation (BIER II) has studied the problem and failed to reach a consensus. The Committee's report was retracted after release of the results at a May 2, 1979 press conference because of dissenting opinions (Marshall, 1979a). The controversy centers on the component of risk directly proportional to dose appropriate for the low-dose range.

The main aspect of the problem is that clinical data on the health effects on humans from low doses of radiation are difficult to obtain. Much data is available for high doses and the range of health affects at these doses is well defined. An assumption is required as to whether or not the same proportionate risk applies at low radiation levels as at high radiation levels. The proportionate risk for low-level effects assumption is described as a linear, no-threshold dose-response and is derived by linear extrapolation of high dose data into the low dose range and supplemented by animals studies, such that the dose-response curve reaches the origin (no dose-no health effects) with a non-zero slope (Figure 2.1). Strong arguments in favor of the linear dose-response curve at low doses have been advanced but agreement has certainly not been reached. Several alternative extrapolations to low doses are also shown in Figure 2.1. Depending on the outcome of this controversy, modifications to Federal regulations for radiation protection may be required.

The most commonly used number gives an augmented probability for eventual cancer death equal to 1/5000th of the whole-body dose equivalent

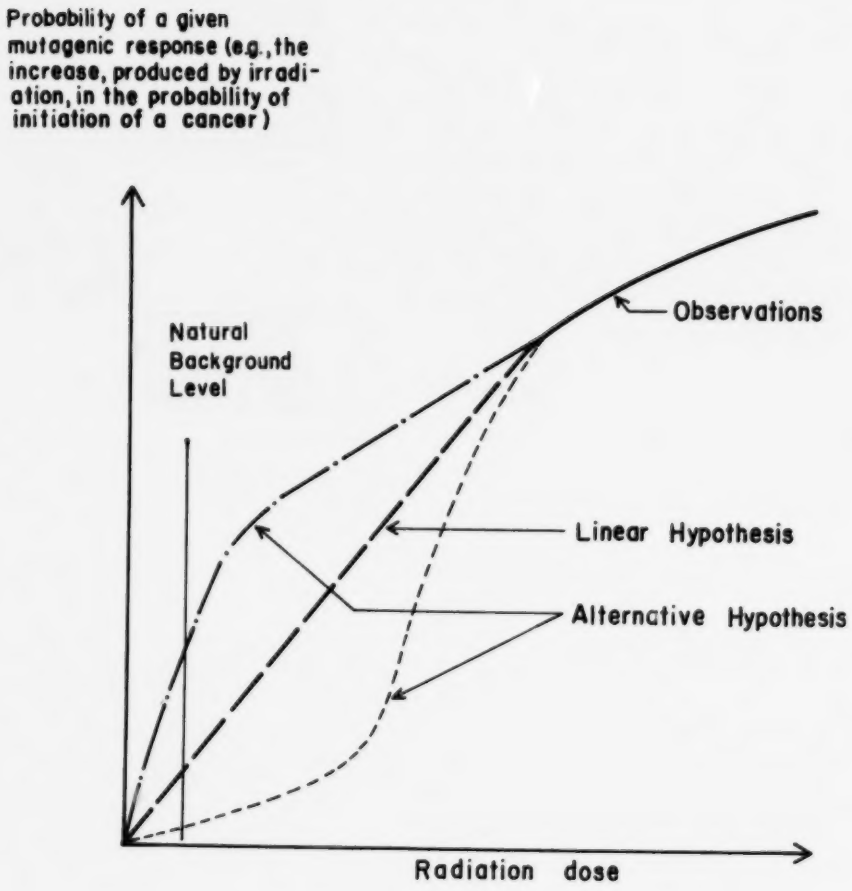

Probability of a given mutagenic response (e.g., the increase, produced by irradiation, in the probability of initiation of a cancer)
Natural Background Level
Observations
Linear Hypothesis
Alternative Hypothesis
Radiation dose

FIG. 2.1 - SCHEMATIC DEPICTION OF CONCEIVABLE POSSIBILITIES FOR THE SHAPE OF THE DOSE - RESPONSE CURVE

SOURCE : Modified from Committee on Literature Survey of Risks Associated with Nuclear Power, 1979.

in rem. This figure is generally accepted as "conservative" when used for design and regulatory decisions even though it is regarded by some as a slight underestimate and by others as a gross overestimate. The corresponding figure for genetic abnormalities from radiation is less certain but thought to be of the same order as for cancer (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979).

CHAPTER 3

REGULATORY FRAMEWORK

The U.S. government owned and operated all atomic energy facilities prior to 1954. The civilian nuclear program began in that year and has been subject to Federal regulation ever since. The Atomic Energy Act of 1954 created the Atomic Energy Commission (AEC) to license and regulate nuclear activities. The Energy Reorganization Act of 1974 created the Nuclear Regulatory Commission (NRC) and transferred AEC's licensing and regulatory functions to the NRC. The role of the NRC and other agencies in the licensing, regulation and setting of radiation protection standards for the civilian nuclear program is described in this chapter. Much of this material has been taken from a review by Peterson and Mattson (1978) as well as from the regulations of the agencies involved.

NRC's basic authorities include licensing and regulation of production, ownership, distribution and use of source materials, special nuclear materials and byproduct materials, and licensing and regulation of the manufacture, production, possession, use, importation or exportation of production and utilization facilities. The NRC defines "source material" as uranium (not enriched), thorium or ores which contain one-twentieth of one percent (0.05%) or more by weight of uranium or thorium. "Special nuclear material" includes plutonium, uranium-233, uranium enriched in the isotope 233 or the isotope 235, any material artifically enriched in these materials and any other material specified by the NRC. "Byproduct materials" include radioactive materials (except special nuclear material) produced in or made radioactive by exposure to radiation incident to the process of producing or utilizing special nuclear material. Simply stated, this means the NRC has authority over virtually every aspect of the nuclear fuel cycle except mining.

However, the NRC is not the only Federal agency with authority to regulate the industry. For example, the U.S. Environmental Protection Agency has authority to set standards for radiation protection of the general environment. These standards were issued in 1979 in 40 CFR, Part 190 and apply to all uranium fuel cycle facilities involved in the generation of electric power except uranium mines, nuclear energy centers, transportation, waste disposal and recycle facilities. The exposure limits set by EPA for a individual member of the public from the planned release of radioactive materials (except radon and its daughters) during normal operation of a fuel cycle facility are: 25 millirem/yr for the

whole-body dose; 75 millirem/yr for the thyroid dose; and 25 millirem/yr for any other organ dose. The EPA also set ceilings on the total quantity of radioactive materials allowed to enter the general environment from the entire uranium fuel cycle, per gigawatt-year of electrical production: 50,000 curies of krypton-85; 5 millicuries of iodine-129; and 0.5 millicuries combined of plutonium-239 and other alpha-emitting transuranic radionuclides with half-lives greater than one year. The EPA also has authority to establish effluent guidelines under the Federal Water Pollution Control Act Amendments of 1972, to specify the maximum contaminant levels in public drinking water under the Safe Drinking Water Act, and to establish air quality standards under the Clean Air Act and its amendments. The NRC sets standards for individual nuclear fuel cycle facilities such that the general public will not be exposed to more radiation than is permitted by the EPA.

Another area in which the NRC shares responsibility is in the transportation portions of the fuel cycle. Both the NRC and the U.S. Department of Transportation (DOT) have authority in this area. Overlaps in authority have been resolved in a series of memoranda of understanding between the two agencies. As it now stands, DOT has authority over classification, labeling and marking of all radioactive material packaging as well as over the carriers and radiation exposure limits for interstate and overseas shipments. The NRC licenses package designs and loading and unloading facilities, investigates accidents and requires that DOT regulations apply to intrastate as well as interstate shipments. More details are given in the section on transportation in the chapter on the nuclear fuel cycle.

The Occupational Safety and Health Administration (OSHA) under the U.S. Department of Labor and the Bureau of Mines (BOM) under the U.S. Department of the Interior have authority over work places and mines, respectively. The radiation protection standards administered by these agencies are generally similar to those of the NRC except for additional reporting requirements.

In addition to sharing regulatory responsibility with other agencies, the NRC may delegate certain authority to the states. Except for the regulation of the construction and operation of production and utilization facilities, the export or import of nuclear materials and certain types of radioactive waste disposal, the NRC may enter into agreements with the governor of a state so that the state may assume regulatory control over source materials, special nuclear materials (in quantities less than a critical mass) and byproduct materials. The state must show that it has a program which is adequate to protect the public health and safety before it can assume this authority. While twenty-five states have entered into such agreements with the NRC, Kentucky is the only state to have done so in the ORBES region.

The NRC has promulgated a set of radiation protection standards which applies uniformly to all stages in the nuclear fuel cycle licensed by NRC. The standards are largely based on the guidelines and recommendations of the Environmental Protection Agency, the National Council on Radiation

Protection and Measurements, the International Commission on Radiological Protection and the former Federal Radiation Council. The standards have been published in Title 10, Code of Federal Regulations, Part 20 and are generally much stricter for individuals in unrestricted areas (i.e., general public) than for individuals in restricted areas (i.e., nuclear facility workers).

The permissible occupational doses are: 1.25 rem/calendar quarter for the whole body, head and trunk, active blood forming organs, lens of eyes or gonads; 18.75 rem/calendar quarter for hands and forearms or feet and ankles; and 7.5 rem/calendar quarter for the skin of the whole body. Individuals under 18 years of age cannot receive doses greater than ten percent of the above limits. In addition, the whole-body dose from radioactive material and other sources of radiation in the licensee's possession shall not exceed 3 rem in any calendar quarter. The dose to the whole body, when added to the accumulated occupational dose to the whole body, may not exceed 5(N-18)rem where "N" equals the individual's age in years at his last birthday. Concentrations of radioactive materials in the air and water of restricted areas are not to exceed the levels specified in Table I of Appendix B of 10 CFR, Part 20.

Concentrations of radioactive materials in the air and water of unrestricted areas are not to exceed the levels specified in Table II of Appendix B of 10 CFR, Part 20.

In addition to these requirements, radioactive effluents routinely discharged to the environment are subject to the "as low as is reasonably achievable" limits as set forth in 10 CFR, Part 50. Design objectives and limiting conditions for operations are provided in detail in Appendix I to 10 CFR, Part 50. The design objectives for liquid effluents are 3 millirem/reactor-year for the dose to the total body from all pathways and 10 millirem/ reactor-year for the dose to any organ from all pathways. Design objectives for gaseous effluents are: 10 millirad/reactor-year for the gamma dose in air; 20 millirad/reactor-year for the beta dose in air; 5 millirem/reactor-year for the dose to the total body of an individual; and 15 millirem/reactor-year for the dose to the skin of an individual. The design objective for radioiodines and particulates released to the atmosphere is 15 millirem/reactor year for the dose to any organ from all pathways.

A further provision of Appendix I calls for the cost-effective control of population dose. Additional equipment for the treatment of effluents over and above that required to reach the design objectives is required until the marginal cost per unit reduction in population dose within 50 miles of the facility exceeds $1,000 per total body person-rem for the whole-body dose, or $1,000 per person-thyroid-rem for the integrated thyroid dose.

Exceptions to these regulations may be granted by NRC if it can be shown that every reasonable effort has been made to minimize effluents and that it is unlikely that any individual in the general population will be exposed to radionuclide concentrations in excess of those specified in Appendix B, Table II of 10 CFR, Part 20.

CHAPTER 4

THE NUCLEAR FUEL CYCLE

INTRODUCTION

It should be noted that the nuclear fuel cycle cannot properly be called a cycle until fuel reprocessing and/or long-term, high-level waste disposal are integrated into the existing system. Nevertheless, the term is used because it is convenient and widely used in the literature.

This chapter contains a separate section devoted to each of the major stages of the fuel cycle as depicted in Figure 1.1. Aspects of the cycle which occur at more than one point in the cycle, such as waste storage, transportation and decommissioning, are treated in sections of their own.

Each section is divided into subsections on background and risks. In the background subsection, the function of each stage in the fuel cycle is briefly described along with an indication as to where the facilities engaged in that stage are geographically located. The locations of facilities in the ORBES region are shown in Figure 4.1 and indicated in the text by a number in brackets immediately following the first mention of the facility. The bracketed numbers correspond to numbers on the map. The background subsections also contain brief introductions to the major current policy issues centered on each stage in the cycle.

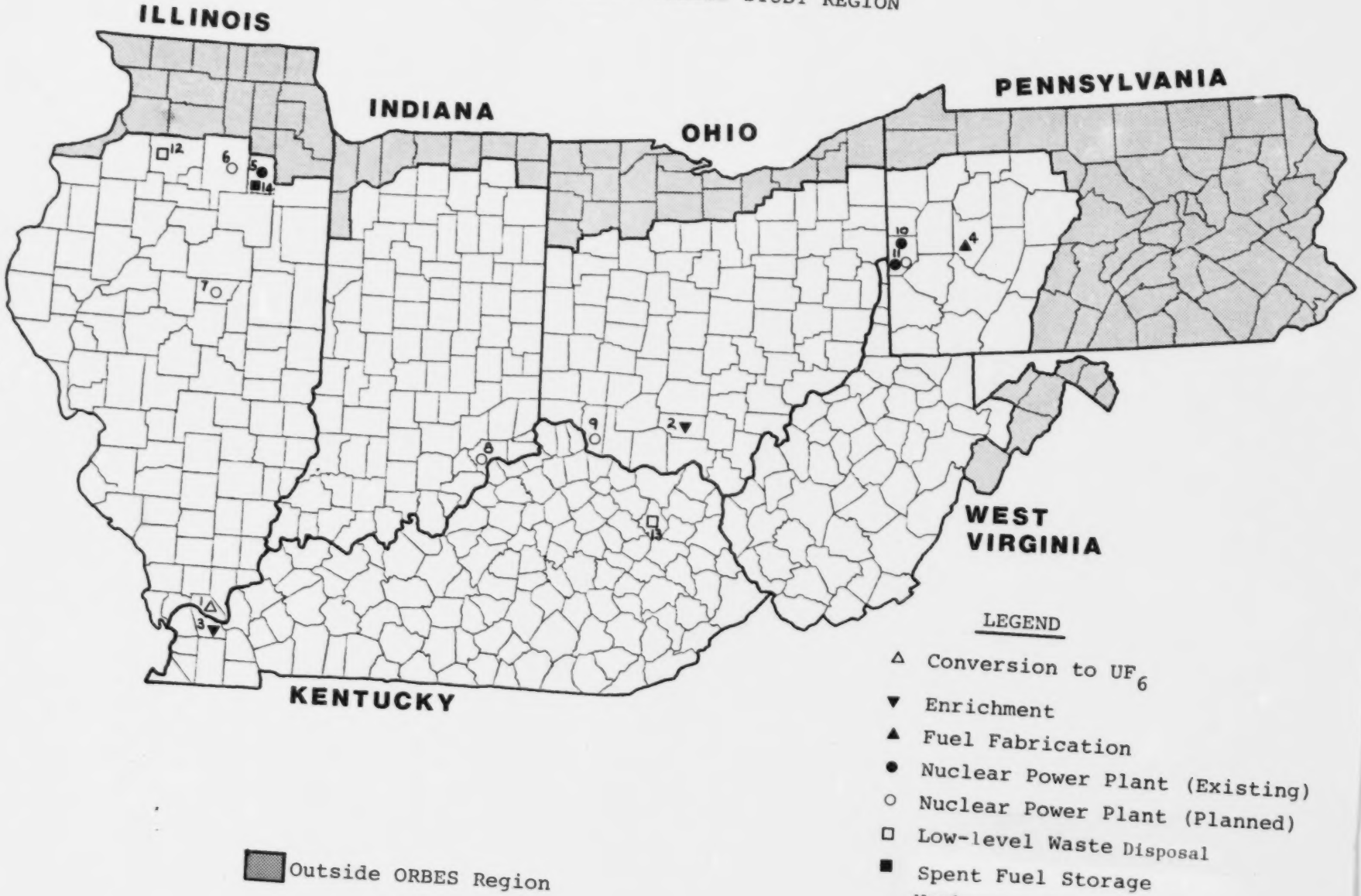
Estimates from the literature on the potential or actual radiation exposure at each stage of the cycle are presented in the subsections on risks. Radiological health effects and other nonradiological health impacts are furnished if available. Where possible, estimates of occupational and general population risks are given separately. At certain stages in the cycle radiological accidents pose hazards which are qualitatively or quantitatively distinct from those posed by normal operation. Separate treatment in the text is warranted in those cases.

Waste generation rates, accident rates, radiation doses and health impacts have been converted to a "per reactor-year" basis where possible. This is a convenient means of presenting diverse types of information in comparable terms. Quantities are given in terms of the amount required by a 1000 MWe light water reactor (LWR) operating at a 65 to 70 percent capacity factor.

Some of the estimated radiation doses presented in the text are accompanied by a measure of the associated health impact. All health

FIGURE 4.1.

LOCATION OF NUCLEAR FACILITIES IN THE
OHIO RIVER BASIN ENERGY STUDY REGION



impact estimates presented have been taken from the literature. Many of these were taken from the Nuclear Energy Policy Study Group (1977) which assumes a "...linear dose-response relation, with a risk factor of 180 cancer deaths per million [person]-rem (whole-body equivalent)..." (p. 173). Meaningful interpretation of health effect estimates is possible only with full knowledge of the assumptions behind the estimates. Estimates from other sources are accompanied by a brief note on the assumptions involved. The original sources should be consulted for further details.

Many of the person-rem dose commitments are not followed by an estimate of the associated health impact. In fact, many of the person-rem estimates are not accompanied by an estimate as to the number of persons exposed. The size of the population exposed is irrelevant if a linear dose-response relation is assumed for low-level radiation health effects. Under this assumption, total person-rem dose is all that is required to determine health effects. In any case, most estimates as to the size of the exposed population are speculative and subject to wide variation. If this information is not provided by the original reference, it is not given in this report.

URANIUM MINING

Background

A 1000 MWe light water reactor (LWR) with a 67 percent capacity factor requires the mining of nearly 100,000 metric tons of 0.2 percent uraniun oxide (U3O8) ore per annual fuel allotment. The uranium content of the deposits currently being mined generally ranges from 0.15 to 0.3 percent uranium oxide (Godbee et al., 1978, p. 8).

In 1977 there were approximately 200 privately owned and operated mining operations responsible for the U.S. production of 10 million tons of ore containing over 14,000 tons of uranium oxide (Berge, 1978, p. 1). Although most of these mines employ underground methods, slightly more than half of the total production is from open pit operations due to higher capacity per mine. Of the uranium ore mined in the U.S., 95 percent is found in sandstone formations, predominantly in the arid west. New Mexico and Wyoming produce about 75 percent of the uranium mined. Colorado, Texas, Utah, and Washington also produce significant tonnage, and Arizona and California have recently started mining uranium. The principal uranium minerals found in the U.S. and their representative occurrence are shown in Table 4.1. There are no uranium mining operations in the ORBES region although the area does contain some currently uneconomic deposits dispersed in coals and shales.

TABLE 4.1. PRINCIPAL URANIUM MINERALS AND THEIR REPRESENTATIVE OCCURRENCES IN THE UNITED STATES

Mineral	Composition	Some Occurrences
Uraninite (Pitchblende)	Uranium oxides	Colorado, Utah, New Mexico
Coffinite	Uranium silicate	Utah, Wyoming
Carnotite	Potassium uranium Vanadate	Colorado, Utah, Arizona, New Mexico
Tyuyamunite	Calcium uranium venadate	Nex Mexico
Torbernite	Copper uranium phosphate	Colorado, Utah
Carbonate-fluorapatite	Calcium fluoro-phosphate containing uranium	Central Florida, Idaho, Utah, Wyoming

SOURCE: Godbee et al., 1978, p. 8.

Risks

The ore deposits currently being mined are often in contact with ground water. On the average, 123 million gallons of water must be pumped out of these mines for surface distribution per 100,000 tons of ore. This figure, of course, varies from place to place (Science and Public Policy Program, 1975). Such effluents contain suspended solids and minute amounts of naturally radioactive elements, primarily those in secular equilibrium with U-235 and U-238. Currently, these effluents are discharged to the environment after settling but without further treatment. They are not considered a health hazard.

Uranium and its daughters are also released to the environment in the form of atmospheric particulates and gases when the ore is exposed and broken during mining. Atmospheric dispersion rapidly reduces the concentration such that the airborne particulate radionuclides approach normal background levels at the site boundary (Radford, 1980, p. 5). For radon gas, however, this assumption may not be correct.

Most earlier studies have concluded that general population exposures from radon decay are negligible because the mines are remote from populated areas (Nuclear Energy Policy Study Group, 1977, p. 174). In contrast, the Final Generic Environmental Statement on the Use of Recycle Plutonium in Mixed Oxide Fuel in Light Water Cooled Reactors (GESMO; USNRC, 1976a) concludes that a whole-body population dose of about 420 person-rem per reactor-year with additional doses to the bone (1370 person-rem per reactor-year) and kidney (1600 person-rem per reactor-year) could result from the 5,000 curies released from the ore mined to supply a reactor for one year. These doses result from the direct decay of radon-222 and decay daughters of radon-222 such as polonium-210 and lead-210 which may enter the human food chain through deposition on crops. About 0.08 delayed deaths per reactor-year are calculated for this whole-body dose when a simple average linear dose-response relation is assumed (Nuclear Energy Policy Study Group, 1977, p. 174). Radford (1980) calculates about 0.01 lung cancer cases per reactor-year as a result of lung dose. Thus, mine emissions are one of the principal contributors to population exposure from the LWR uranium fuel cycle (Committee on Literature Survey of Risk Associated with Nuclear Power, 1979, p. 43).

Uranium miners are exposed to danger from accidents and radiation. Underground miners are at greater risk from both sources. Accidents are responsible for about 15 deaths per 10,000 underground miners or about 0.2 deaths per reactor-year (Nuclear Energy Policy Study Group, 1977, pp. 173-174). Sagan (1972) estimated fatal mining accidents at about 0.1 per reactor-year. Radford (1980) estimates 0.4 deaths from accidents and lung disease and a total of three serious accidents or respiratory disease cases per reactor-year.

Although average concentrations of radon-222 daughters have consistently decreased in uranium mines, the average exposure is still well above the standard and exposure from these sources is considered to be a major source of health effects for underground miners (Radford, 1980, p. 6).

Radon-222 daughters are short-lived radioactive isotopes which are absorbed on dust particles and which, when inhaled, are potentially carcenogenic. The GESMO report gives lung dose commitments of about 960 person-rem per reactor-year and a whole-body dose of 175 person-rem per reactor-year (USNRC, 1976a). Pochin (1976) estimated 100 person-rem per reactor-year for external whole-body dose in mines. Using an average linear dose-response relation, this lung dose gives 0.04 delayed fatalities (at 40 deaths per million person-rem) per reactor-year and Pochin's whole-body dose gives 0.02 delayed cancer fatalities per reactor-year (Nuclear Energy Policy Study Group, 1977, p. 174). Radford (1980) estimates a total bronchial dose commitment of about 5000 person-rem per reactor-year resulting in a total lifetime lung cancer risk of 0.6 per reactor-year, to which are added 0.06-0.09 excess cancers from whole-body exposure.

URANIUM MILLING

Background

The process of uranium milling concentrates uranium from the ores to produce a semi-refined uranium oxide product called yellowcake (80% U_3O_8). The mill extraction of U_3O_8 is nearly 95 percent efficient and involves complex processing which includes crushing, grinding, leaching, separation, purification, precipitation and final thickening of the yellowcake. The large volume of ore that needs to be hauled to the mill constrains the mills to be located near the mine. The production of one pound of uranium oxide produces about 400 pounds of tailings. These tailings are the undissolved solids which are discharged from the mill along with nearly uranium-free process water and process chemicals. The tailings which remain in the tailings pond after evaporation contain about 85 percent of the radioactive material originally in the ore (American Physical Society Study Groups on Nuclear Fuel Cycles and Waste Management, 1978, p. S165). Military and civilian programs have produced a combined total of over 140 million tons of mill tailings. Nearly 100,000 tons of tailings are produced each year to satisfy the fuel needs of one 1000 MWe reactor. At present there are 22 mills (Table 4.2) with a combined annual production capacity of over 26,000 metric tons of U_3O_8. There are no milling operations in the ORBES region.

Risks

The radioactive decay chain of thorium-230 (half-life of 76,000 years) in tailings produces radon-222 which is the major source of environmental exposure associated with uranium milling. At distances greater than 0.5 miles from even large piles, the dose is reduced to near background levels (American Physical Society Study Group on Nuclear Fuel Cycles and Waste Management, 1978, p. S79). However, the inappropriate use of tailings as foundation fill material has resulted in indoor radon concentrations thousands of times higher than background.

The GESMO study estimates that dried and stabilized tailings covered with two feet of earth contribute about 10 person-rem to annual whole-body

TABLE 4.2. URANIUM MILLING COMPANIES AND PLANTS

Company	Plant location	Nominal capacity, metric tons per day (TPD)	Remarks
The Anaconda Company	Grants, New Mexico	4,600	To expand to 6,000 TPD by early 1979
Atlas Corporation	Moab, Utah	1,500	
Continental Oil Company-Pioneer Nuclear, Inc.	Falls City, Texas	2,900	
Cotter Corporation	Canon City, Colorado	450	To expand to 1,000 TPD
Dawn Mining Company	Ford, Washington	400	
Federal-American partners	Gas Hills, Wyoming	1,000	
Exxon-Nuclear Company, Inc.	Powder River Basin, Wyoming	3,000	
Kerr-McGee Nuclear Corporation	Grants, New Mexico	7,000	
Petrotomics Company	Shirley Basin, Wyoming	1,500	
Rio Algom Corporation	La Sal, Utah	750	
Union Carbide Corporation	Uravan, Colorado	1,300	
Union Carbide Corporation	Gas Hills, Wyoming	1,200	
United Nuclear-Homestake Partners	Grants, New Mexico	3,600	
Utah International, Inc.	Gas Hills, Wyoming	1,100	
Utah International, Inc.	Shirley Basin, Wyoming	1,100	
Western Nuclear, Inc.	Jeffrey City, Wyoming	1,250	To expand to 2,000 by 1980
Sohio Petroleum Company	Bibo, Nex Mexico	1,660	
United Nuclear Corporation	Church Rock, New Mexico	3,000	
Western Nuclear, Inc.	Wellpinit, Washington	2,000	
Bear Creek Uranium Company	Douglas, Wyoming	1,000	
Lucky Mc Uranium Corporation	Gas Hills, Wyoming	1,200	To expand to 2,000
- Do -	Shirley Basin, Woming	1,800	

SOURCE: Berge et al., 1978.

population dose-commitments. This rate of exposure is not large on an annual basis but accumulates to about a 1,000 person-rem commitment per century. This translates into 0.2 latent cancer deaths per century for each reactor-year of operation based on average linear dose-response estimates (Nuclear Energy Policy Study Group, 1977, p. 175). Ellett and Richardson (1976) give slightly higher estimates.

The American Physical Society (1978) reports that radon emissions from tailings can be reduced by over 98 percent by using clay lined ponds covered by ten inches of clay. In 1978 Congress passed the Uranium Mill Tailings Radiation Control Act which designated the U.S. Environmental Protection Agency as the agency responsible for setting standards for control of such waste disposal facilities. The schedule for control measures was published in the February 28, 1979 Federal Register.

Ore crushing and grinding release radioactive particulates and radon gas. These emissions are vented to the atmosphere at rates of about 75-85 curies per reactor-year (Atomic Energy Commission, 1972b; and Radford, 1980). The GESMO estimates, which appear to include those from active tailings piles, are about ten times higher and give a general population whole-body dose equivalent of about 100 person-rem per reactor-year with additional doses to the bone (273 person-rem per reactor-year) and the kidney (315 person-rem per reactor-year). The average linear dose-response estimate for this whole-body dose amounts to about 0.02 latent cancer deaths per reactor-year (Nuclear Energy Policy Study Group, 1977, p. 175). A lung dose of 67 person-rem was calculated by Radford (1980) to result in 0.009 lung cancers per reactor-year among the general population.

Mill workers generally receive less than 600 millirem per year of external whole-body radiation and total lung exposures similar to those of miners (Radford, 1980, p. 11). The GESMO estimates a lung dose commitment of about 700 person-rem which, according to an average linear dose-response relation, could be expected to result in 0.03 delayed cancer fatalities per reactor-year (Nuclear Energy Policy Study Group, 1977, p. 175). The estimates from Radford (1980) indicate a 300 person-rem dose to the lungs which would result in 0.04 delayed lung cancers per reactor-year. The Committee on Literature Survey of Risks Associated with Nuclear Power (1979, p. 40) gives an estimate for bone dose at 224 person-rem per reactor-year and for the whole-body commitment at 56 person-rem per reactor-year. Radford (1980) estimates 6 person-rem for the whole-body commitment. Accidents in uranium mills are responsible for about 0.001 deaths per reactor-year.

CONVERSION TO UF6

Background

This step involves refining and converting yellowcake to readily volatilized uranium hexafluoride (UF6) which is the feed for isotopic enrichment. The conversion process is nearly 100 percent efficient. There are two conversion plants in the U.S.: one is in the ORBES region at Metropolis, Illinois (owner and operator: Allied Chemical) [1] and the other at Gore, Oklahoma (Kerr-McGee Nuclear). The dry hydrofluor plant at Metropolis has a UF6 production capacity equivalent to about 14,000 metric tons of uranium per year, and the wet solvent extraction plant at Gore has an annual capacity of 9,090 metric tons of uranium conversion. A third plant with a capacity of 23,500 metric tons per year is proposed for a site near Carlsbad, New Mexico (Becker Industries).

Risks

Yellowcake delivered to a conversion plant contains 80 percent U3O8 and 20 percent waste solids. Among the waste materials are a number of naturally occurring nuclides, mostly U-238 and Th-230 decay daughters. These are confined to the process liquid residuals and are either impounded on the plant site or released to a receiving stream. Radioactive materials in liquid effluents released to the environment, to date, never have been measured at more than 4 percent of the levels permissible under Federal statutes (Science and Public Policy Program, 1975). The actual amounts of radioactivity released to the aquatic environment during the conversion process is minute. Gaseous effluents in plant exhaust air contain even smaller amounts of radioactivity. Small amounts of radioactive ash residue are packaged and sent to licensed low-level, commercial disposal sites.

The GESMO study estimates the whole-body lifetime dose commitment for the general public due to conversion to be about 7 person-rem with a bone dose of 17 person-rem and kidney dose of 2 person-rem per reactor-year. Conversion facility workers are estimated by the same study to have a whole-body lifetime dose commitment of one person-rem with a bone dose commitment of 224 person-rem and a lung dose commitment of 6 person-rem per reactor-year (USNRC, 1976a). Radford (1980) estimates an average whole-body dose commitment per individual worker to be about 0.2 rem/yr with critical organ dose commitment of about 3 rem/yr to the lungs and about 2.2 rem/yr to the bone. On the assumption of 80 workers per nominal plant, Radford's estimates give a whole-body dose of 16 and a lung dose of 240 person-rem per reactor-year.

ENRICHMENT

Background

Natural uranium contains only 0.715 percent fissile or fissionable isotope U-235 and 99.285 percent U-238. Uranium fuel for modern LWRs is enriched to about 3 percent of U-235 content by means of the gaseous diffusion process. The equivalent of just over 5 percent of the electricity generated by a light water reactor is required to enrich the fuel for that reactor by this process (Committee on Nuclear and Alternative Energy System, 1979, p. 235). Enrichment facilities are owned by the Department of Energy (DOE), licensed by the NRC and operated by private companies. There are currently three enrichment plants in the U.S.: two are in the ORBES region at Portsmouth, Ohio (Goodyear Aerospace Corporation) [2] and Paducah, Kentucky (Union Carbide Corporation) [3]; the third is located at Oak Ridge, Tennessee (Union Carbide Corporation). All three plants were built between 1943 and 1955 and work in tandem. The Paducah plant produces a 1 percent enriched gas for shipment in the solid state to Oak Ridge and Portsmouth where gases of higher enrichment are produced (3 to 98%). Enrichment processes are quite efficient with 99.95 percent of the feed uranium being accounted for either as depleted feed or enriched gas. The plan to expand the Portsmouth facility by installation of gaseous centrifuges, which are less electricity intensive but more capital intensive than the existing diffusion enrichers, is currently being reviewed (Inside D.O.E., 1980b).

Risks

About 0.002 curies/yr of uranium in gases and 0.01 curies/yr of uranium in liquids are released in the enrichment process per reactor-year (Radford, 1980, p. 16). Doses to the public and to employees from these releases are extremely small as long as fuel is not recycled (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979). Radford (1980) estimates a whole-body dose commitment of 25 person-rem per reactor-year.

CONVERSION TO FUEL

Background

In this step, uranium dioxide (UO_2) is produced from enriched UF_6 and is then pulverized and formed into small pellets, about one centimeter in diameter and 15 centimeters long. The process is about 99 percent efficient at converting UF_6 into UO_2. Fuel rods, about four meters long, are then fabricated by placing sintered UO_2 pellets in zirconium alloy tubes in which both ends are closed with welded plugs. A large LWR contains about 40,000 fuel rods which are bundled into fuel rod assemblies at the fabrication facilities. A typical assembly for a pressurized water reactor (PWR) consists of a 15x15 array, while the fuel rods are assembled into 7x7 or 8x8 arrays for a boiling water reactor (BWR). The average annual fuel materials requirements for a typical 1000 MWe LWR is shown in Figure 4.2.

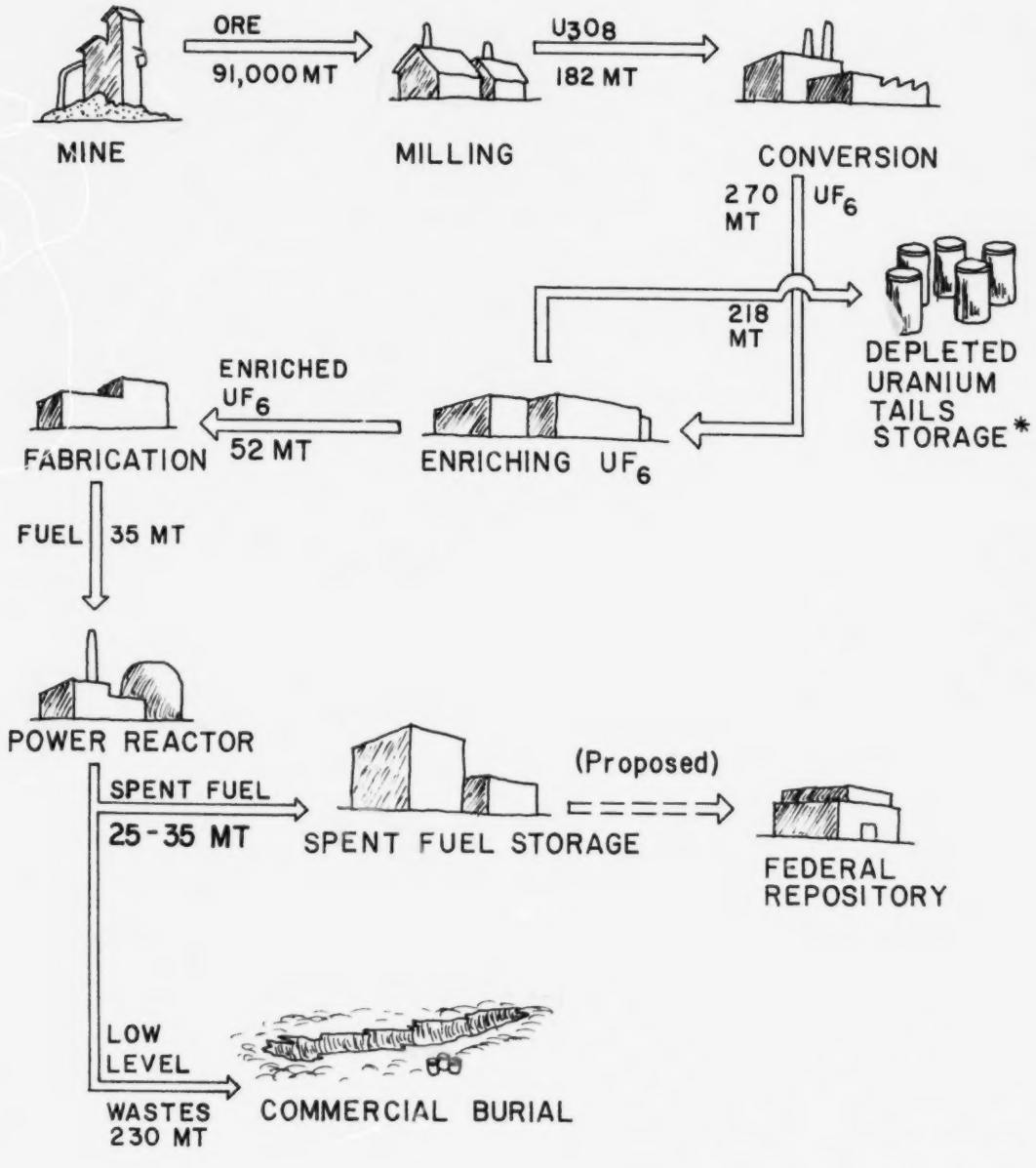


FIG. 4.2 - Average Annual Fuel Materials Requirements for a Typical 1000 MWe Light Water Reactor (metric tons)

SOURCE: Congressional Research Service, 1977, p.378.

* Not required for reactor but must be stored safely. Has value for future breeder reactor blanket.

The powder/pellet and fabrication facilities in the U.S. are shown in Table 4.3. All are licenced by the NRC but owned and operated by private companies. There are three powder/pellet facilities and seven fuel fabrication facilities in the U.S. The ORBES region has a combination powder/pellet and fuel fabrication facility at Apollo, Pennsylvania [4].

Risks

The radiological effluents from fuel fabrication facilities consist of about 0.002 curies/yr of uranium in gaseous form, 0.013 curies/yr of uranium and thorium-234 in liquids, and 0.23 curies/yr of uranium in solids per reactor-year (Radford, 1980, p. 18). The GESMO study estimates fuel fabrication contributions to lifetime whole-body dose commitment of the general public at 0.4 person-rem per reactor-year, a bone commitment of 7 person-rem per reactor-year, and a kidney commitment of 1.1 person-rem. The GESMO estimates for employees are 8 person-rem to the whole body and 323 person-rem to the lungs per reactor-year (USNRC, 1976a). Radford (1980, p. 18) estimates occupational exposures to produce an annual whole-body dose commitment of about 0.20 rem per worker for a total of 100 person-rem and a lung commitment of about 9.95 rem per individual for a total of 5000 person-rem per reactor-year. Radford's estimates translate into 0.02-0.04 excess cancer cases from the whole-body dose and 0.6 lung cancers due to the lung dose.

REACTOR

Background

Nuclear power reactors are complex devices designed for the controlled release of energy from uranium fuel by fission reactions. The released energy heats water to produce steam which is expanded through a turbine. The turbine is linked to a generator which produces electricity.

As of March 1980, there were 72 operating commercial power reactors in the U.S. with a total capacity of 53,241 MWe, 89 reactors (97,762 MWe) with construction permits, two reactors (2,300 MWe) with limited work authorizations, and 19 reactors (22,232 MWe) on order (Atomic Industrial Forum, 1980). These plans indicate that by 1995 or so there may be 182 reactors with a total capacity of over 175,000 MWe. However, these figures may be high since this same source reported in January 1976 that there were 228 reactors operating, under construction or in various stages of the planning process.

In the ORBES region there were five operational reactors at the end of 1979 with a combined total capacity of 2,810 MWe. Eight reactors are scheduled for the period between 1980 and 1986. The location of the reactors in the ORBES region and their operation schedule is displayed in Table 4.4 as taken mainly from Jansen (1978). The total nuclear power capacity in the ORBES region will be 10,821 MWe by the year 1988 if these plans are realized. A detailed list of the reactors in the non-ORBES portion of the six ORBES states is given in Appendix A.

TABLE 4.3. POWDER/PELLET AND FABRICATION FACILITY LOCATIONS

Fabrication Facilities

Babcock & Wilcox Company	Lynchburg, Virginia
Combustion Engineering, Inc.	Windsor, Connecticut
Exxon Nuclear Company	Richland, Washington
General Electric Company	Wilmington, North Carolina
Kerr-McGee Corporation	Cimarron, Oklahoma
NUMEC Division - Babcock & Wilcox Company	Apollo, Pennsylvania [4]
Westinghouse Electric Corporation	Columbia, South Carolina

Powder/Pellet Facilities

Combustion Engineering, Inc.	Hematite, Missouri
Nuclear Fuel Services, Inc.	Erwin, Tennessee
NUMEC Division - Babcock & Wilcox Company	Apollo, Pennsylvania [4]

SOURCE: Congressional Research Service, 1977; and Berge et al., 1978.

TABLE 4.4. REACTORS LOCATED IN ORBES REGION

State and Utility	Plant and Map No.	Location	MWe	Type/Mfr	Operable Date and Status
ILLINOIS					
Commonwealth Edison Co.	Dresden 1 [5]	Morris	209	BWR/GE	1960
Commonwealth Edison Co.	Dresden 2 [5]	Morris	828	BWR/GE	1970
Commonwealth Edison Co.	Dresden 3 [5]	Morris	828	BWR/GE	1971
Commonwealth Edison Co.	LaSalle 1 [6]	Seneca	1,078	BWR/GE	1980 (C)
Commonwealth Edison Co.	LaSalle 2 [6]	Seneca	1,078	BWR/GE	1981 (C)
Illinois Power Co.	Clinton 1 [7]	Clinton	950	BWR/GE	1982 (C)
Illinois Power Co.	Clinton 2 [7]	Clinton	950	BWR/GE	1988 (C)
INDIANA					
Public Service Indiana	Marble Hill 1 [8]	Madison	1,130	PWR/W	1982 (LWA)
Public Service Indiana	Marble Hill 2 [8]	Madison	1,130	PWR/W	1984 (LWA)
KENTUCKY					
NIL					
OHIO					
Cincinnati Gas & Electric Co.	W.H. Zimmer 1 [9]	Moscow	810	BWR/GE	1980 (C)
Cincinnati Gas & Electric Co.	W.H. Zimmer 2 [9]	Moscow	1,150	BWR/GE	1989 (Indefinitely postponed)

TABLE 4.4. REACTORS LOCATED IN ORBES REGION (Contd.)

State and Utility	Plant and Map No.	Location	MWe	Type/Mfr	Operable Date and Status
PENNSYLVANIA					
Duquesne Light Co.	Shippingport [10]	Shippingport	60	LWBR/W	1977
Duquesne Light Co.	Beaver Valley 1 [11]	Shippingport	885	PWR/W	1978
Duquesne Light Co.	Beaver Valley 2 [11]	Shippingport	885	PWR/W	1984 (C)
WEST VIRGINIA					
NIL					

Note: C - Construction Permit
O - Order
LWA - Limited Work Authorization
BWR - Boiling Water Reactor
PWR - Pressurized Water Reactor
LWBR - Light Water Breeder Reactor
GE - General Electric
W - Westinghouse

SOURCE: Jansen, 1978 and unpublished updates.

Risks

Up to the point of reactor operation, all radionuclides encountered, such as U-238, U-235 and their decay daughters, are of natural origin. Fission in the reactor is accompanied by the accumulation of radioactive fission products and the transformation of coolant and structural materials to radioactive forms by neutron absorption. These materials do not normally occur in nature, although a particularly rich vein of uranium ore in Gabon is known to have gone critical, consumed a portion of its fuel, and created the spectrum of products characteristic of fission nearly two billion years ago (Cowan, 1976, p. 36). Risks can be conveniently divided into those from normal reactor operation and those projected for reactor accidents.

Normal Reactor Operation

A small amount of the fission products and neutron activated materials are released to the air and water during normal reactor operation. These are discussed in this section. Other potential radiation hazards created during reactor operation are discussed in other sections of this report. The risks associated with neutron activated reactor components, which must safely be disposed of, are treated under the section on decommissioning. Spent fuel disposal is included in the section on waste storage. The discussion in this section is limited to fission products which migrate from the fuel into the cooling water through cladding defects, neutron activated cooling water (tritium) and other radioactive impurities which reach the environment during normal reactor operation.

Pressurized water reactors (PWRs) and boiling water reactors (BWRs) release different amounts of potentially harmful radioactive materials because of their different operating conditions. Radford (1980) reports that in 1976, PWR noble gas (krypton-85, xenon-133 and xenon-135) emissions ranged from a few up to 15,000 curies per reactor-year while BWR emissions varied from 30,000 to more than a million curies per reactor-year. Another study reported that about 500 curies of krypton-85 are released annually from an average LWR (Nuclear Energy Policy Study Group, 1977, p. 176). The global health risk of such a release is estimated at about 7×10^{-5} deaths per reactor-year (Ellett and Richardson, 1976).

Iodine-131 is released in both its gaseous and liquid forms and is considered a major concern from an environmental standpoint because it is readily taken up by the thyroid gland. Radford (1980, p. 21) reports that measured releases of iodine-131, with a half-life of eight days, vary from several millicuries to 100 curies per reactor-year. Some small particulates also escape through air filtering systems. It is estimated that in 1974, on the average, 0.5 curies per reactor-year were emitted from PWRs and 1.1 curies per reactor year from BWRs (Radford, 1980).

Tritium is produced primarily by neutron activation but also by tertiary fission. Tritium is released as both a liquid effluent (90%) and as gaseous water vapor (10%). Radford (1980) reports that PWRs release about 1000 curies per reactor-year and BWRs release about 100 curies per reactor-year.

Neutrons interact with oxygen-17 and nitrogen-14 in the cooling water and fuel of reactors to produce carbon-14. Radioactive carbon-14 is of concern because of its long half-life (5,730 years) and the fact that it is readily incorporated into biological material. The GESMO estimates indicate that about 10 curies per reactor-year could be released to the environment with a population whole-body commitment of about 50 person-rem per reactor-year (USNRC, 1976a). An average linear dose-response relation gives an estimated 0.01 latent cancer fatalities per reactor-year for this whole-body dose (Nuclear Energy Policy Study Group, 1977). Ellett and Richardson (1976) estimate 0.09 delayed fatalities per reactor-year based on a 100-year environmental dose commitment. The magnitude of the long-term hazard due to carbon-14 is uncertain because the paths by which it reaches man are not well understood. The Committee on Literature Survey of Risks Associated with Nuclear Power (1979) concluded that the future population dose from reactor operation is expected to be dominated by carbon-14.

Based on estimates given by the Committee on Literature Survey of Risks Associated with Nuclear Power (1979), reactor operation will contribute 89 person-rem per reactor-year to the whole-body lifetime dose commitment of the general population with additional doses to the bone (365 person-rem) and thyroid (137 person-rem).

Workers at nuclear reactors are subject to risk from accidents (primarily during construction) and radiation (primarily during operation). Pochin (1976) estimates four construction fatalities per plant while Sagan (1972) reports two for 1969. Workers are exposed to radiation primarily during refueling, maintenance, inspection and waste treatment. According to the American Physical Society Study Group (1978), an average occupational dose of 400 to 500 person-rem was typical of the exposure involved in operating a reactor for one year during the period 1973-1975. The Committee on Literature Survey of Risks Associated with Nuclear Power (1979) reports a lifetime, whole-body dose commitment for employees of 868 person-rem. This is in substantial agreement with the Nuclear Energy Policy Study Group (1977) which reports that "[d]ata for existing plants indicate that occupational dose commitments are about 800 [person]-rem per reactor-year, with variations of up to a factor of 2" (p. 177). The report goes on to calculate a latent cancer incidence of 0.15 per reactor-year associated with this dose commitment based on an average linear dose-response relation. This report also states that recent data suggests that exposures increase with plant age because of equipment activation and accumulated contamination. The American Physical Society Study Group (1978) claims that the data show no clear trend on this issue at the present time.

Radford (1980) analyzed exposures of workers at LWRs for the years 1969 through 1977. In 1976 an average of 669 persons per commercial LWR received measurable exposure. Since 1972 the average exposure has remained about constant at 0.7-0.8 rem/yr with those workers receiving 5 rem or more remaining about one percent of the total exposed workforce. Standards for exposure set by the NRC are frequently exceeded in terms of both short-term exposures and average annual exposures. Wide variability

in exposure results from different reactors. Figures for 1976 show average exposures in the range of 0.2 to 1.7 rem for PWRs and 0.4 to 2.2 rem for BWRs. Variability within a plant is a function of job assignment. For example, health physicists responsible for radiation protection and maintenance workers are exposed to higher individual doses than operating personnel. Radford concludes that average annual exposure figures are not good indicators of the individual worker's potential risk.

Reactor Accidents

Many studies have been conducted to address the issue of reactor safety. The most detailed of these to date has been variously called the Rasmussen report (after the director of the study), the Reactor Safety Study or WASH-1400 (USNRC, 1975). The idea of risk, as defined in the Reactor Safety Study, involves both the likelihood and consequences of an event. The Reactor Safety Study took the view that serious public health consequences could result only from reactor accidents which involved the melting of the reactor core and breach of the containment building housing the reactor. It is necessary for the core to melt before large amounts of radioactivity can be released because about 98 percent of the radioactivity is confined within the fuel as long as the fuel is adequately cooled. Overheating and melting of the core can occur in one of two ways: through a loss-of-coolant accident (LOCA); or through transients in which the core generates more heat than the cooling systems can remove (USNRC, 1975, pp. 21-22).

The study used the event-tree methodology to identify significant accident sequences leading to core melt and the fault-tree method to identify the various combinations and sequences of other failures that lead to a given failure. Elements in the fault-tree were assigned probabilities based on limited amounts of operational experience from the nuclear safety research program, from judgment, or from non-nuclear experience with similar components, such as pumps, pipes, valves, relays and diesel generators.

The Reactor Safety Study concludes that the risks to the public from potential accidents in nuclear power plants are low compared to risks from non-nuclear accidents like fires, explosions, toxic chemical releases, dam failures, airplane crashes, earthquakes, hurricanes and tornadoes. Some of the estimates of the study are as follows:

- The probability of a core melt accident is one in 20,000 per reactor-year. The chances of such a core melt causing deaths, injuries, latent fatalities, thyroid nodules and genetic damage are each less than one per reactor-year. Property damage is estimated at less than one million dollars per reactor-year;

- The probability of an accident resulting in ten or more fatalities is about one in three million per reactor-year;

- The probability of an accident resulting in 100 or more fatalities is one in ten million per reactor-year;

- The probability of an accident resulting in 1000 or more fatalities is one in 100 million per reactor-year; and

- The worst accident considered has a probability of one in a billion per reactor-year and would result in 3,300 prompt deaths and cause radiation damage to another 45,000 people, many of whom would eventually die of the induced cancers.

Critiques of the Reactor Safety Study abound. The major findings of some of these are given here. The American Physical Society, who commissioned an earlier report on reactor safety (American Physical Society Study Group on Light-water Reactor Safety, 1975), while finding merit in the analysis, expressed doubt about the reliability of the absolute probability calculations of the Reactor Safety Study. The Environmental Protection Agency (EPA) conducted a review of the study which concluded that the overall methodology was useful but that differences in site-specific circumstances were not adequately accounted for and that health effects were underestimated by a factor of from one to several hundred (USEPA, 1976). The EPA also commissioned an independent review by Intermountain Technologies, Inc. which concluded, among other things, that the study incompletely or improperly considered the risk impact of human reliability (Davis, 1976). Strong negative criticisms have come from the Sierra Club who, in cooperation with the Union of Concerned Scientists, state that the study underestimated the probability of reactor failures by factors ranging from ten to 100, depending on the severity of the accident (Kendall et al., 1977).

The NRC sponsored a study by the Risk Assessment Review Group (1978) to review and make recommendations on the Reactor Safety Study risk assessment methodology with a view toward clarifying its use in the licensing and regulation of reactors. The Group found that "[d]espite its shortcomings, the study provides at this time the most complete single picture of accident probabilities associated with nuclear reactors. The fault-tree/event-tree approach coupled with an adequate data base is the best available tool with which to quantify these probabilities" (p. viii). They also concluded that although they could not tell whether the absolute probabilities of the study accident sequences are high or low, the error bounds on those estimates are, in general, greatly understated in their opinion. The NRC accepted the recommendations of the Risk Assessment Review Group that the overall risk estimates of the study should not be used uncritically either in the regulatory process or for public policy purposes (Hendrie, 1979).

The Nuclear Energy Policy Study Group (1977) summarizes many of the problems with the Reactor Safety Study methodology. Some of these are given below:

- Unknown or unsuspected failure mechanisms cannot be included, causing risks to be underestimated;

- Some probabilities are based on judgment rather than experience;

- Some redundant back-up safety systems are assigned independent probabilities of failure when they may not actually be independent since some "common mode" failures can increase the likelihood of failure of one system once another has been disturbed;

- The study averaged results over a sample of reactor sites so that the results are not applicable to individual reactor sites; and

- Terrorism and sabotage were not considered.

WASTE STORAGE

Background

Over two million cubic meters of nuclear wastes have accumulated as a result of the country's military and civilian nuclear programs (Interagency Review Group, 1979). Nearly 80 percent of the volume of this waste has resulted from military programs and about 20 percent from civilian nuclear programs. In the civilian programs, radioactive wastes are generally divided into two groups: high-level wastes comprised of the heavy metals associated with spent fuel and the highly radioactive portion of reprocessing waste streams; and low-level wastes comprised of materials which have absorbed less radioactivity such as contaminated clothing, trash and sweepings. Of the total waste volume, the high-level wastes constitute about 12 percent (99% military and 1% civilian) and the low-level wastes constitute about 88 percent (76% military and 24% civilian). In terms of radioactivity, the high-level commercial wastes accumulated to date are comparable to defense waste at about one billion curies each (White House, 1980). Due to a growing waste generation rate in the commercial nuclear reactor industry and a nearly constant defense-related waste generation rate, the commercial sector has now generated more total wastes (in terms of cumulative radioactivity) than the military sector (Interagency Review Group, 1979, p. 8). The military and civilian programs have produced a combined total of over 140 million tons of uranium mill tailings which are accumulating near the mills in the West. The annual waste generation rates for a typical LWR operating under normal conditions are shown in Table 4.5.

The hazardous nature of these wastes combined with the long period over which some of them remain hazardous requires a well conceived and executed system of storage and ultimate disposal or long-term care. However, it should be noted that, whatever the future of the commercial reactor industry may be, a waste system is still required for the commercial and defense wastes that have been generated in the past and the defense wastes that will likely be generated in the future (Committee on Nuclear and Alternative Energy Systems, 1979, p. 317). The purpose of mentioning military waste here is not to focus on that issue but to put the commercial waste issue in perspective.

TABLE 4.5. ANNUAL WASTE GENERATION RATES

(Normalized to an Average 1000 MWe LWR) [1]

Generated Onsite		
Spent Fuel Discharged	25.4	metric tons
	(9.4	cubic metres)
Low-Level Waste [2]	1,274	cubic metres
Generated Offsite		
Uranium Mill		
Tailings Solutions [3]	254,000	metric tons
Tailings Solids [4]	96,000	metric tons
UF6 Conversion	34	cubic metres
Enrichment [5] [6]	1.4	cubic metres
Fuel Fabrication	21	cubic metres

[1]Assuming a "once through" fuel cycle (no reprocessing), an average capacity factor of 67 percent, a thermal efficiency of .32, an average burnup of 25,000 MWD/MTHM, and that 1/3 of the reactors are BWRs and 2/3 are PWRs.

[2]Roughly 40 percent of current volumes generated is contaminated trash.

[3]These wastes are currently disposed of at the processing facility site.

[4] Ibid.

[5] Ibid.

[6]This value is based on gaseous diffusion technology. The new centrifuge process could potentially generate more (up to 82 cubic metres/yr).

SOURCE: Modified from Interagency Reveiw Group, 1979, p. D-6.

High-level Wastes

The high-level wastes currently being generated in this country by the commercial sector consist almost entirely of spent fuel assemblies that have served their useful function in the core of a nuclear reactor. Technically only "those aqueous wastes resulting from the operation of the first cycle solvent extraction system, or equivalent, and the concentrated wastes from subsequent extraction cycles, or equivalent, in a facility for reprocessing irradiated reactor fuels" can be condidered as high-level wastes (10 CFR 50, Appendix F). Only a small portion of all spent fuel has been reprocessed to date. However, the high-levels of radioactivity in spent fuel along with President Carter's 1977 decision to indefinitely defer commercial reprocessing for non-proliferation reasons warrant consideration of spent fuel as high-level waste at the present time. Reactivation of the reprocessing option could change the classification of spent fuel from a waste to a fuel resource as long as the fuel assemblies are stored in a retrievable form. Spent fuel is currently being stored in "swimming pools" at the reactor sites in retrievable form. The absence of reprocessing, the lack of a federal repository for high-level wastes, and inadequate storage capacity at the reactor sites have created a need for some kind of Away From Reactor (AFR) surface storage facilities in the next several years (Carter, 1979). President Carter's AFR policy is flexible in that it gives adequate time to consider alternative federal repository designs and sites while not foreclosing the reprocessing option.

Three commercial nuclear fuel reprocessing plants have been built in the U.S.: Nuclear Fuel Services at West Valley, New York; General Electric at Morris, Illinois (ORBES region); and Allied General Nuclear Services at Barnwell, South Carolina. None are currently operating. The Morris facility [4] was never operated as a reprocessing plant because General Electric encountered technical problems in making it work properly (Gustafson, 1979, p. 31). The Morris plant has received spent fuel from commercial plants in California, Connecticut, Wisconsin and Illinois. It has the capacity to store about 750 metric tons of spent fuel. As of September 1979, the Morris plant had received about 310 metric tons of spent fuel. The West Valley plant is the only commercial facility which has reprocessed spent fuel in this country. Between 1966 and 1972, 620 metric tons of spent fuel were reprocessed and another 170 metric tons of spent fuel were received but not reprocessed (Godbee, et al., 1978, p. 19). The plant was shut down for expansion in 1972 but changes in regulations made expansion economically unjustifiable. The reprocessing plant at Barnwell has never been licenced to receive spent fuel. The Morris facility is the prime candidate for the first AFR spent fuel storage facility and Barnwell and West Valley are also under consideration (Inside D.O.E., 1980a, p. 3).

High-level wastes, whether in the form of spent fuel or reprocessing wastes, must ultimately be disposed of by some permanent, although possibly retrievable, means. The Department of Energy (DOE) has responsibility for developing long-term management programs for radioactive nuclear wastes (Office of Nuclear Waste Isolation, 1979). In 1976 DOE

established the National Waste Terminal Storage Program (NWTS) to carry out the technical and institutional investigations necessary for the permanent isolation of nuclear wastes.

The technical feasibility of many disposal options has been investigated and several demonstration projects were initiated but have since been terminated before completion. The Atomic Energy Commission (AEC) abandoned its Lyons, Kansas demonstration project in 1971 after the Kansas Geological Survey and individual citizens found unexplained water movements, which the AEC had not found, in a salt formation less than a half-mile from the proposed waste facility (Abbotts, 1979, p. 14). President Carter recently cancelled the Waste Isolation Pilot Plant (WIPP) although investigations of the bedded salt formations near Carlsbad, New Mexico are continuing (Carter, 1980).

The Interagency Review Group on Nuclear Waste Management (1979) identified six candidate technologies for the disposal of high-level wastes and transuranic wastes:

- Placement in mined repositories
- Placement in deep ocean sediments
- Placement in very deep drill holes
- Placement in mined cavity in a manner that leads to rock melting
- Partitioning of reprocessing waste, transmutation of heavy radionuclides and geologic disposal of fission products
- Ejection into space.

Of these, the mined geologic repository could be available the earliest, with the others either available 10-15 years in the future (deep ocean sediments and deep drill hole disposal) or much later because of scientific, engineering or institutional problems. The Department of Energy (DOE) analyzed these and other options and also reached the conclusion that conventional geologic disposal could be brought to commercial operation earliest but not in less than 10-15 years (USDOE, 1979a, p. 4.12). The Interagency Review Group (1979, p. 38) found that there is adequate scientific and technological knowledge to proceed with site characterization and region selection. The Committee on Nuclear and Alternative Energy Systems (CONAES, 1979, p. 316) and the American Physical Society Study Group on Nuclear Fuel Cycles and Waste Management (1978) reached essentially the same conclusion that existing technological knowledge is adequate to establish confidence in geologic disposal of wastes. These two groups also agree that, at this time, spent fuel should not be classified as waste due to its residual energy content. The U.S. Geological Survey emphasizes, however, that "[c]onstruction of a repository and emplacement of waste will initiate complex processes that cannot, at present, be predicted with certainty" (Bredehoeft et al., 1978, pp. 12-13).

CONAES (1979, p. 316) goes on to state that political and institutional barriers must be overcome before implementation of any radioactive waste disposal option. These include obstacles due to public perception of risk, the failure to agree on which agency should set standards (DOE or NRC), the failure to agree on the need for a demonstration facility before a working repository is designed and the unresolved question of waste retrievability. President Carter recently established the State Planning Council on radwaste management which may help resolve some of these issues. The State Planning Council will have 18 members composed of the heads of the Department of Energy and the Environmental Protection Agency, a representative from an Indian tribe, eight governors and five other state and local officials (Carter, 1980). This group is designed to help the Administration carry out its policy of "consultation and concurrence" in the siting of high-level waste repositories. Allowing state and local officials to take an active part early in the site selection process may ameliorate some of the local opposition encountered in the past when sites have been proposed. States would not have veto power over the site selected (Carter, 1980). The problem of siting is illustrated by the fact that 11 states have already prohibited the burial of radioactive wastes within their jurisdictions and 15 additional states are considering similar measures (Martin, 1978).

Low-level Wastes

Low-level wastes result from miscellaneous processing and include such items as tools, machinery, clothing and other materials contaminated with relatively small amounts of radioactivity during nuclear plant operations. These wastes contain less than ten nanocuries of transuranic contaminants per gram of material and have potentially hazardous but low concentrations or quantities of radionuclides which require little or no shielding (Interagency Review Group, 1979 p. 10). The current disposal practice for such wastes is land burial in shallow, unlined trenches. Following the recommendations of the Interagency Review Group (1979), DOE is considering other options which include disposal in the ocean, in mine caverns or in concrete-lined trenches (Inside D.O.E., 1979, p. 5).

There are six low-level waste disposal sites in the U.S., three of which are now closed (Table 4.6). Two of these sites are in the ORBES region: Sheffield, Illinois [12] and Maxey Flats near Morehead, Kentucky [13]. The Sheffield site became operational in 1967 and was abandoned in April 1978 when the site was filled to capacity and the operating company decided that the site had become unprofitable because of state regulations and suits concerning state regulations. Although the site is state owned, both the County Circuit Court and the NRC have ruled that the site must remain in the care of the operating company (Chicago Tribune, 1979, p.2). The site at Maxey Flats went into operation in 1963 and was closed in December 1977 after radiation well below the standard for drinking water was detected in surface water off-site and further geologic investigations revealed fissures that might allow contamination of ground water.

The site at West Valley stores low-level wastes in addition to the high-level wastes mentioned above. Low-level wastes have leaked from this

TABLE 4.6. LOW-LEVEL COMMERCIAL WASTE BURIAL SITES

Operator	Location	Year Operation Began	Volume (1000 meters^3) buried as of 1/1/77[d]
Nuclear Engineering Co.	Sheffield, Ill.[12][a]	1967	87.4[e]
Nuclear Engineering Co.	Richland, Wash.	1965	14.3
Nuclear Engineering Co.	Beatty, Nev.	1962	55.2
Nuclear Engineering Co.	Maxey Flats, KY.[13][b]	1963	133.6[f]
Nuclear Fuel Services	West Valley, N.Y.[c]	1963	68.9
Chem-Nuclear Services, Inc.	Barnwell, S.C.	1971	98.6
		TOTAL	458.00

(a) Closed April 8, 1978

(b) Closed December, 1977

(c) Closed March 11, 1975

(d) Includes commercial transuranic waste

(e) As of April 8, 1978

(f) As of December, 1977

site to nearby streams. There is an ongoing controversy as to who is responsible for cleaning up the site. The three remaining low-level waste sites at Barnwell, South Carolina, Beatty, Nevada and Richland, Washington are operating now but were temporarily closed in the Fall of 1979 by the governors of those states to protest the improper packaging of shipments and the disproportionate share of the waste disposal burden being borne by these states (Marshall, 1979b).

Risks

High-level Wastes

A LWR with a capacity of 1000 MWe discharges annually about 25 to 35 metric tons of spent fuel, depending on the annual megawatt-hour output and the design. Each ton contains 30 kilograms of highly radioactive fission products and slightly less than 10 kilograms of transuranic elements, including about eight kilograms of plutonium. The remainder is "unburned" uranium containing about 0.8 percent U-235. The fission products involve a number of different isotopes including strontium-90, cesium-137, technetium-99, iodine-129 and krypton-85. Many of these isotopes are extremely hazardous and must be handled remotely. All spent fuel is stored for at least a period of several months at the reactor site to allow sufficient time for the isotopes with short radioactive half-lives (such as iodine-131) to decay. Careful remote handling of these highly radioactive fuel assemblies at the reactor sites has resulted in no significant public or occupational exposure (Nuclear Energy Policy Study Group, 1977).

Once the spent fuel rods have "cooled" for a period of time at the reactor site, they will either remain on-site until reprocessing or ultimate disposal takes place, or they will be moved to an Away From Reactor (AFR) storage facility. The DOE (1979b) has done an extensive analysis of the impact of a model AFR facility. The model AFR has the capacity to store 3000 metric tons of heavy metal spent fuel for at least 6.5 years in water basins. The facility also incorporates a 2000 metric ton heavy metal/yr capacity packaging plant to prepare the spent fuel for extended storage or disposal. The estimated annual whole-body population dose to the approximately 2 million persons living within an 80-km radius of the plant in the year 2000 would be about 0.03 person-rem from operation of the AFR. The estimated annual doses to the thyroid, lung and bone are 0.47, 0.12 and 0.02 person-rem, respectively. The comparable whole-body dose due to naturally occurring sources is given as about 200,000 person-rem. The 70-year whole-body dose to the surrounding population is given as 1.4 person-rem. Based on 100 to 800 health effects postulated per million person-rem exposure, no health effects are calculated for the regional population due to the operation of the AFR. The work force is expected to receive an annual whole-body dose of 120 person-rem and a 70-year dose of 3,600 person-rem. All estimates include doses from routine releases and minor accidents. One fatality and 110 disabling injuries due to accidents during facility construction are estimated. The maximum dose to an individual from the most severe accident analyzed is estimated to result in an exposure which is about equal to exposure from background radiation and is therefore considered to be insignificant.

The next step in the storage of high-level radioactive waste is long-term isolation. The fission products in spent fuel remain significantly radioactive for periods up to about 500 years but actinides (elements with atomic numbers 89 through 103) are of concern for periods on the order of 100,000 to a million years. As mentioned earlier, the candidate disposal option which at the present time appears to offer the best isolation of these wastes for long time periods and the option most discussed in the literature is deep underground burial at geologically suitable sites.

Many geologic media have been investigated, including salt, granite, shale and basalt. Most designs call for canisters containing the solidified waste to be placed in a mined repository at a depth of about 500 to 600 meters below the surface. Once the repository has been filled and sealed, there are only two credible ways in which the radionuclides can be returned to the biosphere--by exposure of the rock mass containing the wastes or by dissolution of the wastes by ground water and subsequent discharge at the surface (Interagency Review Group, 1979, p. 44). The probability of exposure of the rock mass is quite small if appropriate siting criteria are applied; therefore, ground water dissolution is the most likely mechanism of transfer to the biosphere (Interagency Review Group, 1979; and Committee on Literature Survey of Risks Associated with Nuclear Power, 1979). Ground water motion is generally quite slow and, in most situations, ion exchange and adsorption of ions on solid surfaces will allow radionuclides to migrate at only a small fraction of the velocity of the ground water. All studies which have attempted to quantitatively evaluate the human dosage due to leaching by ground water have concluded that such dosages, integrated over all time, are not likely to exceed those associated with the normal operation of the rest of the fuel cycle (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979). Another study concluded that gradual leaks from repositories would, at most, increase local radioactivity to twice background levels (USNRC, 1976b).

DOE (1979b) has estimated the impacts on human health and the environment from geologic disposal. The study analyzed 800-hectare reference spent fuel repositories in four media: salt with a capacity of 47,000 metric tons heavy metal; shale with a capacity of 63,000 metric tons heavy metal; granite with a capacity of 126,000 metric tons of heavy metal; and basalt with a capacity of 126,000 metric tons of heavy metal. The smallest of these reference facilities would be capable of storing about 1800 reactor-years of spent fuel and the largest about 5000 reactor-years of spent fuel. Workers are estimated to receive an annual whole-body dose during construction due to naturally occurring radioisotopes of 0.026 person-rem for salt, 720 person-rem for granite, 880 person-rem for basalt and 270 person-rem for shale. The 70-year whole-body doses for workers in mines are calculated at 0.18 person-rem for salt, 5040 person-rem for granite, 6160 person-rem for basalt and 1916 person-rem for shale. Corresponding general population doses due to mining are a factor of ten to a factor of 100 lower. Nonradiological accidents could be responsible for an estimated high of 38 fatalities and 1800 disabling injuries for basalt or an estimated low of nine deaths and 440 disabling injuries for salt. The other two media fall between these extremes.

Normal operation of the reference repositories is estimated to result in vanishingly small radiological exposure to the general population. Workers would be expected to receive a 70-year whole-body dose of 4300 person-rem for salt, 11,000 person-rem for granite, 5600 person-rem for shale and 11,000 person-rem for basalt from normal operation.

The DOE study also analyzes the possible effects of repository breach by various means. A meteorite striking the repository could cause as many as 60,000 adverse health effects. Breach by drilling would probably result in limited doses of about 40 to 250 times background to a few people. Breach by faulting and flooding could also result in serious health consequences. Although the health consequences of repository failure could be quite severe, most studies have concluded that the probability of failure is so low that the associated risks are small (Nuclear Energy Policy Study Group, 1977).

Low-level Wastes

Low-level wastes have a relatively low-level of radioactivity compared to high-level wastes, but may pose a bigger problem because of their huge volume. Low-level radiation usually does not cause measurable damage but may eventually have adverse effects that are not fully understood at present. The question of health effects of low-level radiation is one of the most important unresolved scientific issues concerning nuclear power.

TRANSPORTATION

Background

Transportation of potentially hazardous radioactive materials is required at many points in the nuclear fuel cycle. A summary of the material movements along with the mode of transport and packaging requirements is given in Table 4.7. This table includes the reprocessing step which is currently not part of the cycle. Irradiated fuel is now stored at the reactor sites but will eventually require shipment either to reprocessing facilities or to a Federal repository. The annual amounts of radioactive material requiring transport at each stage of the fuel cycle are shown in Figure 4.2 for a 1000 MWe LWR.

The transportation of radioactive materials is regulated by both NRC and the Department of Transportation (DOT). The NRC has jurisdiction over the shipment of intermediate and large quantities of radioactive materials. DOT has responsibility for setting standards for classification, labeling and carrier operations and for the regulation of small quantity shipments (Peterson and Mattson, 1978, p. 121). Accidents have occurred during shipment of commercial radioactive wastes (Grella, 1976; Shappert, 1974; and U.S. Atomic Energy Commission, 1972a), but no injury, fatality or radioactive release has been observed because of strict packaging requirements and other precautions (Gablin and Garner, 1978, pp. 330-331).

TABLE 4.7. TRANSPORTATION OF RADIOACTIVE MATERIALS IN THE NUCLEAR FUEL CYCLE

Radioactive Material	Point-to-Point Movements	Mode of Transport	Required Packaging
Uranium or thorium ore	Mine to mill	Open truck	None
Ore concentrates (Uranium or thorium products)	Mill to refining and conversion plant	Truck	Drums
Thorium nitrate[1]	Refining plant to materials processing plant	Truck	Drums
Natural UF_6	Refining and conversion plant to enrichment plant	Truck	Pressurized cylinders
Enriched UF_6	Enrichment plant to materials processing plant	Truck	Pressurized cylinders and protective packaging
Uranium (233[1] or 235) or plutonium oxides[2] (fissile)	Materials processing plant (or fuel reprocessing plant) to fuel fabrication plant (may be at same site)	Truck (if offsite)	Steel pails or sealed metal cans within gasketed steel containers supported inside steel drums
Thorium oxide[1] (fertile)	Materials processing plant to fuel fabrication plant	Truck	Drums
New fabricated fuel assemblies	Fuel fabrication plant to nuclear power reactors	Rail[3] or truck	Special fuel element shipping containers
Transuranic wastes	Fuel fabrication plant (or mixed oxide fuel reprocessing plant) to Federal repository[4,5]	Rail[3] or truck	Drums and protective packaging
Irradiated fuel[6]	Nuclear power reactor to fuel reprocessing plant	Rail[3] or truck	Specially designed and approved shielded casks
Recovered thorium[a]	Fuel reprocessing plant to storage	1)	1)
Recovered enriched UF_6 (recycle)	Reprocessing plant to enrichment plant (or materials processing plant)	Truck	Pressurized cylinders and protective packaging
Recovered uranyl nitrate	Fuel reprocessing plant to fuel fabrication plant or conversion plant (or materials reprocessing plant)	Tank trucks or tank cars	Protective packaging
High-level solid wastes	Fuel reprocessing plant to Federal repository[4]	Rail[3] or truck	Specially designed and approved shielded casks
Low- and intermediate-level	From essentially all parts of the fuel cycle to commercial burial grounds	Truck	Drums and protective packaging

1) To the present there has been limited experience in shipping uranium-233 and thorium compounds;
2) To the present there has been limited experience in shipping plutonium compounds;
3) Trucking to railhead may be necessary.
4) The Federal repository is at present nonexistent.
5) Currently shipped to burial grounds.
6) Currently stored at reactor site.

SOURCE: Godbee et al., 1978, p. 27.

Risks

It is generally agreed that the most significant source of potential radiation exposure in the transportation sector is that associated with the shipment of spent fuel and reprocessing wastes if reprocessing is permitted (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979; Congressional Research Service, 1977; Radford, 1980; and Ross, 1975). The potential hazard involved in shipping spent fuel is due to gaseous and volatile fission products that could escape if the lead-shielded cask and the fuel rods it contains were ruptured and overheated in an accident. The potential hazard in the shipment of reprocessing wastes is from plutonium. Only the shipment of spent fuel by truck is considered below for the following reasons: 1) reprocessing has been deferred; 2)transportation of spent fuel to Away From Reactor (AFR) storage facilities seems likely; 3) most spent fuel is shipped by truck; and 4) transportation at other stages of the fuel cycle present insignificant radiological hazards by comparison.

The most serious releases associated with a spent fuel shipment accident are those of cesium-134 and cesium-137 (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979, p. 84; and Ross, 1975, p. 141). Most studies have concluded that for a typical shipment, on the order of ten curies of these species could escape into the atmosphere. Under these conditions an accident would cause immediate radiation fatalities within a few tens of meters of the truck and would lead to no more than a few ultimate cancer deaths even in a densely populated area (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979, p. 84).

Another study by Ross (1975) gave far higher estimates by concluding that 7500 curies of cesium would be released over a period of several hours by such an accident. Assuming a population density of 1000 persons per km^2, the population dose would be 4×10^6 person-rem which could result in roughly 700 additional cancer deaths over 25 years (Ross, 1975, p. 154).

The U.S. Atomic Energy Commission (1974) did a study which combined the probabilities of transportation accidents with the expected consequences of the most severe accidents in low population areas. The results indicate that there would be less than 10^{-10} deaths among the general public per reactor-year of operation. Rose et al., (1976) estimated that the transportation of nuclear fuel would result in 0.045 total fatalities, comprised of 0.010 radiation related deaths and 0.036 deaths from other causes, for each 1000 MWe plant-year of operation.

The occupational exposure to a truck driver is about 15 millirem for a 500-mile haul, including the time spent working near the cask (Radford, 1980). A 1000 MWe reactor requires about 20 spent fuel shipments per year for a total of 10,000 miles traveled per nominal plant per year. As long as this work load is spread over a sufficient number of drivers, the exposure should be well within acceptable limits (Radford, 1980, p. 29).

DECOMMISSIONING

Background

Radioactive facilities must eventually be decommissioned when it is judged that they have reached the end of their useful life. The facilities which require careful decommissioning include nuclear power reactors, spent fuel storage facilities and fuel reprocessing facilities (if they are integrated into the cycle). The focus here is on power reactors since 1) there is a great deal of literature on the subject, 2) there has been prior experience with small reactors, and 3) other facilities pose similar problems.

The technology for decommissioning nuclear reactors is relatively well-developed (Smith, Konzek, and Kennedy, Jr., 1978, p. 3-3). To date, numerous small research and demonstration reactors and five reactors between 50 and 256 MWt have been decommissioned. Although the largest of these is smaller than the average commercial reactor by about a factor of ten, the experience gained has been valuable from the standpoints of developing the necessary technology and understanding the nature of the risks. The 58 MWt Elk River Reactor is one of the largest reactors to be completely dismantled and removed from its site (United Power Associations, 1974). The experience gained with this reactor will be discussed further below.

The NRC regulates the decommissioning activities of its licensees with a view toward protecting the public health and safety and in such a way that the licensees' responsibility to NRC will eventually or immediately be terminated (Nemec, 1978, p. 306). The Atomic Energy Commission (now NRC) identified three acceptable decommissioning alternatives in Regulatory Guide 1.86 (Atomic Energy Commission, 1974) as follows:

Mothballing

"...putting the facility in a state of protective storage. In general, the facility may be left intact except that all fuel assemblies and the radioactive fluids and waste should be removed from the site. Adequate radiation monitoring, environmental surveillance, and appropriate security procedures should be established under a possession-only license to ensure that the health and safety of the public is not endangered."

Entombing

"...sealing all remaining highly radioactive or contaminated components (e.g. the pressure vessel and reactor internals) within a structure integral with the biological shield after having all fuel assemblies, radioactive fluids and wastes, and certain selected components shipped offsite. The structure should provide integrity over the period of time in which significant quantities of radioactivity remain with material in the entombment. An appropriate and continuing surveillance program should be established under a possession-only license."

Dismantling

"All fuel assemblies, radioactive fluids and waste, and other materials having activities above accepted unrestricted activity levels should be removed from the site. The facility owner may then have unrestricted use of the site with no requirement for a license. If the owner so desires the remainder of the reactor facility may be dismantled and all vestiges removed and disposed of."

Numec (1978) discuss these options in detail. Mothballing is a permanent solution only for facilities or components which are not contaminated with long-lived radionuclides. It can be used as a temporary measure to allow radiation levels to decrease prior to final decommissioning. Entombing is likewise a suitable long-term option only if components contaminated with long-lived radionuclides are removed and disposed of separately. Dismantling may start immediately after shut-down or it may be combined with mothballing to provide time for the decay of short-lived radionuclides. Dismantling allows the unconditional reuse of the site and avoids the long-term surveillance and maintenance requirements of the other options. A fourth option is the reuse of the existing turbine system after the original contaminated steam supply system has been decommissioned by one of the other methods.

At the time of shut-down, some components will have become highly radioactive, mainly through neutron activation. Other components will have radioactive characteristics similar to some of the low-level and intermediate-level wastes already generated in the ordinary operation of the fuel cycle (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979).

Risks

The Elk River Reactor produced 53,000 MWd(t) between 1962 and 1968 (United Power Association, 1974). During the dismantling operation, about 100 workers received a total of approximately 75 rem of whole-body penetrating exposure. The maximum whole-body exposure any worker received was about 4.5 rem and the average was approximately 0.8 rem. Smith, Konzek and Kenney (1978, p. 2-9) estimate that the immediate (after shut-down) dismantlement of a 1175 MWe pressurized water reactor of the Westinghouse design will result in an external occupational radiation dose of 1200 person-rem. This figure can be reduced to 760 person-rem or 430 person-rem if the reactor is put in safe storage and then dismantled after ten or 100 years, respectively. Most of the dose included in these latter figures is due to the preparation of the plant for safe storage immediately after shut-down.

Manion and LaGuardia (1976) estimated occupational exposure which are somewhat lower. Their estimates for a generic large pressurized water reactor (PWR) and a boiling water reactor (BWR) are given in Table 4.8.

TABLE 4.8. ESTIMATED OCCUPATIONAL EXPOSURE

	(Person-rem)	
	PWR	BWR
Mothballing	150	80
Entombing	130	125
Dismantling	630	550

The public is not expected to be exposed to radiation except in the transportation phase of decommissioning. Immediate dismantlement is expected to result in transportation exposure of about 22 person-rem spread over a large population (Smith, Konzek and Kennedy, 1978, p. 2-10).

CHAPTER 5

NUCLEAR PROLIFERATION, TERRORISM AND SABOTAGE

PROLIFERATION

Horizontal nuclear proliferation is defined as the manufacture or acquisition of nuclear weapons or other explosive devices by countries which do not now possess them (Hartnett, 1979). Proliferation is a critical and complex problem, mixing elements of nuclear power with international politics and the arms race (Ramsay, 1979). There are three significant proliferation pathways by which the LWR fuel cycle may be used to acquire weapons-usable materials: certain existing enrichment facilities may be used to produce highly enriched uranium; out-of-system enrichment may be used to produce highly enriched uranium; or out-of-system chemical reprocessing may be used to extract plutonium from spent fuel (USDOE, 1979c). The most sensitive proliferation points in the fuel cycle are, therefore, enrichment, spent fuel storage, reprocessing and transportation. Enhanced proliferation resistance of the cycle could be achieved by improved material accounting, containment, surveillance, inspection, reporting and safeguarding of enrichment facilities, spent fuel facilities, transportation and stockpiles of natural uranium and low-enriched uranium (USDOE, 1979c).

Reprocessing is the most sensitive step in the fuel cycle because it provides the most direct link between commercial nuclear power and proliferation. Plutonium from a recycle operation can be used directly in the production of weapons. Reprocessing facilities are susceptible to slow, covert diversion of plutonium which would be difficult for safeguards to detect (US Congress, 1977). Currently, this is not a source of concern in the U.S. in view of the Carter Administration's deferral on reprocessing but other countries are moving ahead with reprocessing.

It is estimated that more than 30 countries will have operating commercial reactors by the mid-1980's, with a total installed capacity of about 300,000 MWe. That would result in the total annual production of plutonium in the cores of these reactors of over 75,000 kilograms which is enough to manufacture 7,500 nuclear bombs (Hartnett, 1979). In addition, a number of these countries are planning the construction or purchase of enrichment facilities, thereby increasing the risk of weapons proliferation.

The International Atomic Energy Agencyy (IAEA), established by the United Nations in 1957, has the responsibility to safeguard sensitive

nuclear materials by setting up and maintaining an international accountability system. The treaty on the Non-Proliferation of Nuclear Weapons (NPT), promulgated by the U.S., Great Britain, and the U.S.S.R., came into effect on March 5, 1970. Since then 100 countries have signed and ratified the treaty. However, some nations that now have, or are likely soon to acquire, nuclear-power or other fission technology installations, have not declared their adherence to the Non-Proliferation Treaty. Some of the nonsignatories to the NPT are France, China, India, Pakistan and Brazil.

TERRORISM AND SABOTAGE

In the late 1960s and the early 1970s the number of bombings of various kinds in the U.S. was running at the rate of about 2,000 a year, with a annual average of 20 to 25 deaths and 170 to 180 injuries involved. None of these incidents involved nuclear weapons (Ramsay, 1979). Some bomb threats and hoaxes have however occurred. There were 38 nuclear hoaxes between 1970 and 1976 (US Congress, 1977). But one has to consider the possibility that future terrorists may gain possession of highly enriched uranium or plutonium for the purpose of making weapons. Terrorists could also disperse plutonium in the air, which could cause cancer if inhaled.

A report from the Office of Technology Assessment (US Congress, 1977) says that a moderately large group of commandos could raid nuclear sites and capture radioactive materials, and also capture weapons stockpiles of the U.S. military. According to a National Academy of Sciences report (Committee on Literature Survey of Risks Associated with Nuclear Power, 1979), it is now generally conceded that a small group of highly intelligent workers, with good technical education and access to the open literature, but without specific prior experience in bomb fabrication, could produce a nuclear device with an explosive yield much greater than that of conventional non-nuclear military weapons. Spent fuel storage facilities are susceptible to sabotage that can result in serious consequences. There might be several ways in which sabotage could disable the safety features of a reactor so as to produce eventual core melting.

The possibilities of theft and clandestine diversion of nuclear materials also exist. There are instances of low-grade and enriched uranium disappearing from nuclear processing plants. Somewhat over 3000 kilograms of bomb-grade material, enough to make hundreds of atomic devices, remains unaccounted for by the U.S. nuclear industry. Some or all of this loss could be due to accounting errors as well as the actual physical loss of material either by accident or direct acquisition by some subnational or international group. The chances of theft and sabotage of bomb-grade materials can be reduced by increased guarding of nuclear facilities.

The Committee on Literature Survey of Risks Associated with Nuclear Power (1979) concludes that risks associated with nuclear proliferation, terrorism and sabotage cannot be quantified by technological analysis alone. Some consider that such risks are small and some insist that they may exceed all others in the nuclear-fuel cycle.

CHAPTER 6

COSTS/BENEFITS: NUCLEAR VS. COAL

INTRODUCTION

In this chapter some of the more important costs and benefits of nuclear power are outlined. Costs and especially benefits are, however, meaningless when considered in isolation. Thus, the approach taken here has been to compare nuclear with coal, the only viable near-term alternative means of producing electricity. As will become evident, a high degree of uncertainty is associated with nearly all of the cost and benefit components discussed.

This chapter emphasizes the economic costs and benefits as well as the relative health impacts of nuclear and coal fuel cycles. Environmental impacts, such as land use changes and thermal effects, have been treated in the main report of the Ohio River Basin Energy Study Phase II.

CAPITAL COSTS: NUCLEAR VS. COAL

One kilowatt of installed nuclear or coal generating capacity is <u>not</u> a homogeneous product. This lack of homogeneity makes it extremely difficult to make definitive statements like; "the price of one kilowatt of installed nuclear generation equals X dollars while that for coal generation equals Y dollars." In a recent book entitled, TOSCA: The Total Social Cost of Coal and Nuclear Power (Gaines, Berry, and Long, 1979), a reasonably large literature was surveyed and it was found that the price per kilowatt for light water reactors varied from 182 dollars to 836 dollars (in 1974 dollars). For coal plants with scrubbers the range was from 162 to 935 dollars/kilowatt and for coal plants without scrubbers the range was from 175 to 565 dollars per kilowatt. There are many reasons for this great variation in cost estimates. Some of those reasons were examined by the Nuclear Energy Policy Study Group (1977). They included estimate variations caused by:

- The basing of estimates upon historically experienced capital costs when much of the early nuclear capacity was heavily subsidized by the producers of nuclear generating equipment;
- Differences among sources with regard to the size of the reference plant and how many of what size units the plants are assumed to consist;
- Geographical variations in labor productivity;

- Geographical variations in safety and environmental regulations which create both differences in the amounts of equipment per kilowatt and also differences in the lengths of the construction periods;

- Geographical variations in the applicable rate of inflation;

- Variations in site characteristics such as seismic risk and cooling options; and

- Different assumptions regarding the definition of capital costs, plant efficiencies, and the characteristics of electricity demand in the area in which the plant will operate.

These and other factors combine to create the large variations indicated earlier. Actually, however, the absolute cost per kilowatt of capacity is not the most meaningful number. What is of greater relevancy is the comparative cost of nuclear vs. coal powered generation. One would expect that by looking at the ratio of coal fired capital cost to nuclear powered capital cost much of the variation induced by the types of factors listed above would be reduced. Table 6.1 indicates precisely that.

Table 6.1 also indicates that the cost to construct coal plants (with or without scrubbers) is less than nuclear plants. Two questions are immediately raised. How have capital costs been changing, and how are they likely to change in the future? Even though there is agreement that nuclear power plant construction costs are higher than was originally anticipated (Nuclear Energy Policy Study Group, 1977, p. 111; and the House Committee on Government Operations, 1978, p. 31), it is much less clear whether the relative construction costs of nuclear plants have been rising vis-a-vis coal plants. For Commonwealth Edison in 1974 it has been reported (Rossin, 1976) that nuclear plants and coal plants with scrubbers cost 420 dollars per kilowatt and coal plants without scrubbers cost 295 dollars per kilowatt. The same author reported that in late 1977 the costs had risen to $692, $638, and $484, respectively (Rossin and Rieck, 1978). This information indicates that for Commonwealth Edison the average annual percentage increase in the nominal (i.e., including general inflation) prices per kilowatt for the years 1974 through 1977 have been 18 percent for nuclear, 15 percent for coal with scrubbers and 18 percent for coal without scrubbers.

Nuclear power generation is much more capital intensive than coal power generation. Chapman (1980) has indicated that the per kilowatt cost for a nuclear plant in 1988 dollars is approximately three times higher than that for a coal plant. Consequently, given the current tax rules relating to depreciation methods, the amount of depreciation utilities are able to exempt from tax liability was also found by Chapman to be about three times larger for nuclear plants. It is unclear, however, whether or not depreciation allowances represent an incentive for building nuclear rather than coal plants, since the financial burden placed upon utilities for the capital requirements of a nuclear plant is also larger than for coal. The larger debt incurred by borrowing for the more capital in-

TABLE 6.1. COMPARATIVE CAPITAL COSTS

(Ratio of Estimated Coal to Nuclear Plant Capital Costs)

	High-Sulfur Coal w/ Scrubbers	Low-Sulfur Coal w/o Scrubbers
Specific Site Estimates		
Northeast Electric (Estimates by ADL/Stoller)	.81	.65
Pilgram 2 (Boston Edison)	.82	---
Millstone 3 (Northeast Utilities)	1.01	.93
Yadkin (Duke Power)	.82	---
Cherokee (Duke Power)	.82	---
Callaway (Union Electric)	.81	.67
Architect - Engineer Estimates		
Bechtel	.83	.74
Ebasco	.91	.69
Other Estimates		
Commonwealth Edison (Plants not Specified)	1.00	.70
WASH-1345	.84	.64
Komanoff (Council on Economic Priorities)	.95	.83
Westinghouse	.83	.71

SOURCE: Nuclear Energy Policy Study Group, 1977, p.123.

tensive nuclear unit may translate into a higher cost of capital for the utility. The decision to build a nuclear or a coal plant thus must balance tax advantages against the problems resulting from incurring a larger amount of indebtedness along with the other cost components reviewed below.

Uncertainties regarding future public attitudes concerning nuclear power as well as the regulatory climate concerning air and water quality make the prediction of the future course of the relative cost of nuclear and coal power plants very difficult and highly speculative. As of now, it appears that the relative cost of constructing a coal-fired generating station is less than a nuclear generating station. Therefore, if a case for nuclear power production is to be made, one must find that justification in other cost categories. It is to those other categories that we now turn.

OPERATION AND MAINTENANCE COSTS: NUCLEAR VS. COAL

Operation and maintenance (O&M) costs consist largely of wages but also include routine repair and other overhead expenses of the utility. Consequently, one would expect to find large regional variations in these costs. Labor productivity and inflation rates vary geographically, causing wage rates to vary accordingly. Due to variable utility emphasis upon unit repair and maintenance, the length (and thus the cost) of unit forced and planned outages will also display regional variation. Since overhead expenses are utility specific, one would expect variation here as well. For light water reactors and coal plants (both with and without scrubbers) one survey (Gaines, Berry, and Long, 1979) has reported O&M costs per kilowatt in 1974 dollars as varying between 6.2 and 11.4 dollars, 13 and 17.6 dollars, and 9.3 and 11.4 dollars, respectively. The reason why the O&M costs for coal plants equipped with scrubbers is uniformly higher than for the other technologies is due primarily to the additional coal handling costs and secondarily to the greater maintenance requirements of scrubbing equipment. One critic of nuclear power generation (Komanoff, 1976) reports estimates of O&M costs for 1984 made by Northeast Utilities. These are $21/kw for nuclear, $32/kw for coal with scrubbers and $16/kw for coal without scrubbers. Deflating these values to 1974 constant dollars for comparison with the ranges previously cited yields $9.39/kw, $14.30/kw and $7.15/kw, respectively. Except for the O&M estimate for coal plants without scrubbers, these numbers are consistent with the ranges specified by Gaines, Berry, and Long (1979).

FUEL COSTS: NUCLEAR VS. COAL

Fuel cost is the sum of mineral mining, beneficiation and transport costs. These costs are generally reported on a basis of per kilowatt-hour generated. Since transport costs vary with distance, fuel costs reported by various sources will also vary. Another source of variation in reported fuel costs is the existence of negotiated long-term contracts for coal and/or nuclear fuel. It is possible that some contracts were executed without fully anticipating actual inflation and without an inflationary clause. Whenever this is the case, fuel cost estimates will tend to understate the real or the opportunity cost of the fuel used. Unfortunately, reported estimates of fuel cost do not indicate whether or to what extent this possible bias affects the numbers. For example, it has been reported (Rossin and Rieck, 1978) that Commonwealth Edison paid 3.5 mills per kilowatt-hour in 1977 for nuclear fuel. This included a one mill per kilowatt-hour set-aside for nuclear fuel disposal. Thus, the actual 1977 out-of-pocket expense for nuclear fuel to Commonwealth Edison was 2.5 mills per kilowatt-hour. This 2.5 mill/kwh figure suggests that Commonwealth Edison was able to negotiate a favorable nuclear fuel contract in the past and thus this figure does not represent the per kilowatt hour replacement cost of nuclear fuel in 1977. Komanoff (1976) uses 8 mills per kilowatt-hour for nuclear fuel in 1984 dollars. This figure was taken from a lecture by Michael Driscoll, Associate Professor of Nuclear Engineering at M.I.T., given July 22, 1976. Correcting this to 1977 dollars for comparison with Rossin and Rieck yields approximately 4.4 mills per kilowatt-hour. Table 6.2 presents, in summary form, nuclear fuel costs and the fuel costs for coal plants with and without scrubbers. The numbers have all been adjusted to 1977 dollars for comparative purposes and represent the available literature. Coal costs vary with the distance it must travel. Additional variance is due to contractual arrangements utilities have with their coal suppliers and to utility ownership of coal mines. In any event, nuclear fuel costs are significantly less than coal.

DECOMMISSIONING COSTS: NUCLEAR FACILITIES

When a coal-fired generating station has outlived its economic life, the utility can simply decommission it in a straightforward manner. This is not true for nuclear facilities because of the radioactivity inherent to the reactor. Consequently, the costs for closing down a nuclear facility must be considered in any economic evaluation. To date, there has been no experience in the decommissioning of large commercial nuclear reactors, although there has been some experience with relatively small research and demonstration reactors (see section on decommissioning in chapter on the fuel cycle). As a result, decommissioning costs for commercial facilities are highly conjectural. The Committee on Government Operations in a highly controversial report (U.S. House Committee on Government Operations, 1978) cites numbers which range from 25 to 100 percent of original capital costs for dismantling and perpetual care. It goes on to say that "no one really knows how much it will cost or who will pay the bill" (p. 22). This lack of knowledge, however, did not prevent the Committee from claiming that "[d]ecommissioning costs therefore repre-

TABLE 6.2. FUELS COSTS: NUCLEAR VS. COAL

(1977 dollars)

Source	Reference Utility Location	Nuclear (mills/kwh)	High Sulfur Coal (mills/kwh)	Low Sulfur Coal (mills/kwh)
Komanoff, 1976	Eastern U.S.	4.4	10.38	11.37
Chapman, Cole, and Slott, 1980	Indiana	7.46	10.48	---
Baughman, Joskow, and Kamat, 1979	N/A	6.32	---	---
Nuclear Energy Policy Study Group, 1977	*	5.75	12.78	16.29
Institute for Energy Analysis, 1979	Midwestern U.S.	4.4	8.86	10.4
Gaines, Berry, and Long, 1979	U.S.	6.76	11.55-12.29	---
Rossin, and Rieck, 1978	Illinois	3.5	8.8	14.1
Roberts, Davis, and Nash, 1978	Midwestern U.S.	6.49	10.07	---

* The Nuclear Energy Policy Study Group used a Midwestern location for the low sulfur estimate and an Eastern location for the high sulfur estimate.

NOTE: For additional detail regarding the methodologies employed by the various sources in deriving their estimates, see the sources.

sent substantial unknown costs of nuclear-generated electricity" (p. 23). The minority opinions published as part of this report emphasize the importance of recognizing that when one is estimating costs to be incurred in the future, the final result will be sensitive to various parametric assumptions (e.g., interest rate and inflation rate). The minority also points out that when decommissioning costs are expressed in mills/kwh, the estimates translate to 0.04 to 1.4 mills/kwh (p. 131) which, they argue, are hardly sufficient to mitigate the nuclear economic advantage.

The Committee on Nuclear and Alternative Energy Systems (CONAES) cites a detailed study of the Atomic Industrial Forum (1976) which concludes that decommissioning costs might be, in constant dollars, as much as 10 percent of the original costs, and CONAES argues that since these can not reasonably be expected to occur for 50 years, discounting them at 5 percent gives a present worth of less than 1 percent of the original plant cost (CONAES, 1979, pp. 271-272). Roberts, Davis, and Nash (1978) also estimated decommissioning cost based upon the Atomic Industrial Forum (AIF) study, but they also compared their results with an NRC commissioned study by Battelle Pacific Northwest Laboratories (Smith, Konzek and Kennedy, 1978) and concluded that Battelle's estimates were "similar to the results in the AIF study" (Roberts, Davis, and Nash 1978, p. 272). In summary, although there is currently no data for full-sized commercial reactors and estimates vary considerably, it does not appear that the cost of decommissioning would seriously influence the relative economics of coal and nuclear power.

HEALTH AND OTHER COSTS: NUCLEAR VS. COAL

Health Costs

The health risks associated with nuclear power production are primarily a result of occupational and non-occupational exposure to radiation. The health risks associated with coal-fired generation of electricity are generally those associated with coal-mining and the air-pollution resulting from burning coal. The American Medical Association Council on Scientific Affairs (1978) has summarized, in tabular form, the work of three widely quoted authorities (Hamilton, 1977; Gotchy, 1977; and Comar and Sagan, 1976). Table 6.3 presents this synthesis. The AMA Council on Scientific Affairs concluded that "at the present time, coal has greater adverse impact on health than does nuclear power production" (p. 2195). A more detailed estimate of the health effects of nuclear power production is contained in the report of the Nuclear Energy Policy Study Group (1977). A summary of their estimates is provided in Table 6.4. This same group concluded that the average rate-of-risk for a 1000 MWe coal-fired plant is about two deaths per year when one does not consider the effects of air pollution. Considering those effects, the rate-of-risk rises substantially and is subject to much more uncertainty but is probably between 2 and 25 deaths per year. If that range of uncertainty appears wide, consider that of Morris (1977) who gave some additional evidence regarding the number of deaths per plant-year attributable to burning coal and nuclear fuel. His figures are summarized in Table 6.5.

TABLE 6.3. ESTIMATES OF HEALTH EFFECTS OF COAL AND NUCLEAR FUEL CYCLES

Procedure	Occupational Deaths[1]	Occupational Injuries and Disease[1]	Nonoccupational Deaths
Coal fuel			
Extraction			
Accidents	0.45 -1.24	22.0 - 80.0	----
Disease	0.00 -4.8	0.6 - 48.0	----
Transport			
Accidents	0.055-1.9	0.33- 23.0	0.55 - 1.3
Processing			
Accidents	0.02 -0.05	2.6 - 3.1	1.0 - 10.0
Power Generation			
Accidents	0.01 -0.03	0.9 - 1.5	----
Air pollution	----	----	0.067-295.0
TOTAL	0.54 -8.0	26.0 -156.0	1.62 -306.0
Nuclear fuel			
Extraction			
Accidents	0.005-0.2	1.8 - 10.0	----
Disease	0.002-0.1	----	----
Transport			
Accidents	0.002-0.005	0.45- 0.14	----
Processing			
Accidents	0.003-0.2	0.6 - 1.5	----
Disease	0.13 -0.33	----	----
Power generation			
Accidents	0.01	1.3	0.01 - 0.16
Disease	0.00 -0.1	----	----
TOTAL[2]	0.035-0.945	3.7 - 13.0	0.01 - 0.16

[1] Per 1,000 megawatt electric unit per year.

[2] Some totals do not add up because of rounding.

SOURCE: American Medical Association Council on Scientific Affairs, 1978, p. 2194.

TABLE 6.4. NUCLEAR HEALTH RISKS

(per 1000 MWe reactor year)

Mining		
Accidents (fatal)		0.15 to 0.20
Accidents (non-fatal)		1100 days
Radiation Exposure (delayed fatalities)		0.06
Radon Emissions (delayed fatalities)		0.08
Milling		
Accidents (fatal)		0.001
Radiation Exposure (delayed fatalities)		0.03
Radon Emissions (delayed fatalities)		0.02
Exposure to Tailing Piles (delayed fatalities)		0.002
Transportation, Conversion, and Fabrication		
Transportation (fatalities)		0.01
Radiation Exposure (delayed fatalities)		0.01
Reactor Facility Construction		
Construction (fatalities)		0.07 to 0.20
Normal Reactor Operation		
Krypton-85, Normal release (delayed fatalities)		0.00007
Carbon-14, Normal release (delayed fatalities)		0.01 to 0.09
Occupational Exposure (delayed fatalities)		0.15
Fuel Disposal		
Public Exposure Risk		Small (unknown)
MAX. TOTAL	=	0.85307
	+	1100 person days lost

SOURCE: Nuclear Energy Policy Study Group, 1977.

TABLE 6.5. MORTALITY IN COAL AND NUCLEAR FUEL CYCLES

(per 1000 MWe plant year)

	Coal	Nuclear
Mining		
Underground-Accidents	0.5-1.1	--
Surface -Accidents	0.2	0.09-0.2
Underground-Diseases	0.2-13	0.04
Processing		
Occupational Accidents	0.04	0.004
Occupational Diseases	--	0-0.03
Transport		
Accidents	0-4	0.01
Electric Generation		
Occupational Accidents	0.01	0.01
Local (80 km) diseases	0-24	0-0.06
Global Diseases	(0-240)	0-0.1
Waste Management		
Diseases	--	0-0.4
TOTALS	0.3-300	0.1-0.5

SOURCE: Morris, 1977.

Radford (1980, p. 33) concludes that from 1.7 to 2.3 excess lifetime cancers occur as occupational hazards in the nuclear fuel cycle. To this morbidity he adds 3 health impacts which he derives from an estimate by Archer, Gillam, and Wagoner (1976) of 0.4 per year excess mortality. Radford assumes morbidity to be at least 8 times mortality. Consequently, on the same assumption, one can gather that Radford's estimates, when translated to mortality data for comparison with the data in Table 6.5, are from 0.6 to 0.7 deaths per 1000 MWe reactor-year.

For the health impacts of the coal cycle, Radford (1980) estimates that the total deaths per 1000 MWe coal plant vary from 7.2 to 14.6 per year. Radford concludes that risks to the general public are 20-30 times greater for coal generation than for nuclear, and occupational risks are twice as great.

The results presented in Tables 6.3, 6.4 and 6.5 take into account the possibility of nuclear accidents, translating the statistics into expected number of deaths per reactor-year. Virtually every one of the above comparisons relied to an extent upon the NRC's Reactor Safety Study which has been criticized as having underestimated accident probabilities (see section on reactor accidents in the fuel cycle chapter). Another, and potentially more serious problem, is that a segment of the public sees an essential difference between the risk of a nuclear accident and other risks. As Ramsay (1979) has pointed out, "[c]atastrophes are qualitatively different from routine small risks, and it is not irrational to view them as being so" (p. 53).

Other Costs

In addition to the health effects of power production for which direct comparisons between coal and nuclear fuel cycles can be made, coal-fueled power production also leads to other environmental effects resulting from air pollution. Ramsay (1979) cites evidence which categorizes these effects as property damage, crop and plant damage, and visual degredation.

The property damage results from chemical deterioration of paint, metal and other surfaces. Ramsay claims these damages, when normalized to a 1000 MWe coal-fired plant, amount to between $700,000 and $7 million per year (Ramsay, 1979). This translates to 20 cents to 2 dollars per month for the average monthly electric bill. Ramsey estimates the crop damage resulting from a new 1000 MWe coal-fired plant to be equivalent to a monthly add-on to the average electric bill of between 7 cents and 70 cents (Ramsay, 1979, p. 22). Monetary estimates of the damage to non-crop plants were not made by Ramsay but were noted. Another source estimated property damage, inclusive of crop damage, acid mine drainage, subsidence and other mine related phenomenon, at 30 million dollars per plant-year maximum and 3 million dollars per plant-year as most reasonable (Gaines, Berry, and Long, 1979). The visual degradation is caused to a great extent by excessive levels of particulates and nitrogen dioxide in the air, much of which results from coal-fired power plants. The effect is difficult to quantify to any precision but certainly represents some cost

to society (Ramsay, 1979). More thorough treatments of other costs associated with electricity production can be found in other ORBES documents.

SUMMARY COMMENTS

If, in comparing nuclear to coal technology, one considers only the costs to build and operate a power plant, then for some sites the nuclear option is more economically attractive and for others the coal option is more economically attractive. Unfortunately, the nature of these technologies is such that there are additional costs (economic and noneconomic) which are as yet unknown and thus create a great degree of uncertainty regarding the total cost of power generation for both nuclear and coal. For the nuclear option the uncertainties primarily concern spent fuel disposal, decommissioning and safety. For the coal option the uncertainties primarily concern the environmental and health consequences of the coal fuel cycle. Thus, depending upon the site location, the methods used by the utility to estimate and value the various uncertain cost components mentioned above and the particular political factors that affect utility decision-making, one technology may be preferred to another. What is more likely and is in fact reflective of current utility planning is that, given these uncertainties, no one technology, but rather a mix, will be relied on for baseload generation.

CHAPTER 7

THREE MILE ISLAND

INTRODUCTION

On March 28, 1979, the worst accident involving a commercial nuclear power reactor in the U.S. occurred at Three Mile Island Unit 2 near Harrisburgh, Pennsylvania. Most investigators agree that, with the possible exception of the psychological impact, public health effects will be small. Nevertheless, the events which began on that day have stimulated a major reevaluation of the future of nuclear power in this country. Nuclear critics have had some of their worst fears confirmed. Nuclear proponents point to the accident as evidence that the system works in spite of multiple failures. The nuclear industry and the Nuclear Regulatory Commission (NRC) have been criticized from all sides for their accident preparation and their accident response.

A flurry of reports issued in the wake of Three Mile Island (TMI) have clarified the sequence of events involved in the accident, pointed out deficiencies in many aspects of electricity production by nuclear means, and made recommendations for the correction of these deficiencies. The major findings of these reports along with the responses of the NRC, the industry and the public are summarized below.

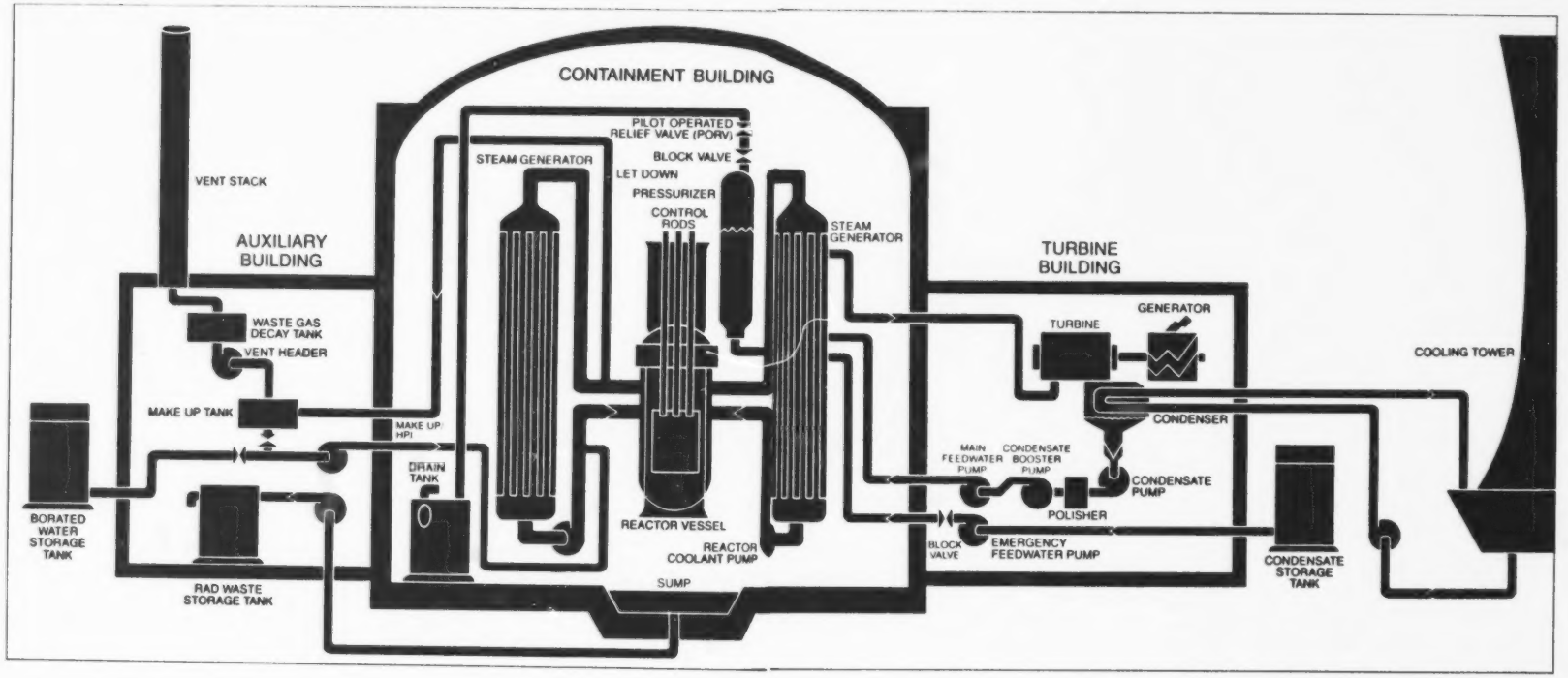
SEQUENCE OF EVENTS

Background

The understanding of the events at TMI-2 requires a basic working knowledge of reactor components and their functional relationships to each other. The TMI-2 facility is schematically depicted in Figure 7.1. The unit was designed by the Babcock and Wilcox Company as a 927 MWe pressurized water reactor (PWR). The main components of the system are:

- The reactor core housed in the reactor vessel with its fuel rods, control rods and instruments;
- The primary coolant system which circulates cooling water through the reactor core and the steam generators;
- Two steam generators in which the primary coolant system water gives up some of its heat to water in the separate secondary coolant system;

FIGURE 7.1 SCHEMATIC OF THREE MILE ISLAND - UNIT 2



SOURCE: President's Commission on the Accident at Three Mile Island, 1979, pp. 106 - 107.

- The secondary coolant system which circulates water through the steam generators, the turbine, the condenser and back to the steam generators;

- The pressurizer attached to the primary coolant system which maintains system pressure;

- A turbine through which steam in the secondary coolant loop is expanded to drive a generator to produce electricity; and

- Pumps to circulate water through the many systems.

Distilled water containing a small amount of boric acid is heated in the reactor core by the fission chain reaction in the uranium fuel rods. The fuel rods are sheathed in cladding made of a zirconium alloy. Under normal conditions, the radioactivity produced in the uranium fuel pellets is contained in the fuel rods by the cladding. The water is heated to about 575 degrees Fahrenheit and kept from boiling by the pressurizer which maintains the primary coolant loop at a pressure of about 2200 pounds per square inch. The pressurizer consists of a large vessel which is about half full of water and half full of steam. The pressurizer controls system pressure by heating or cooling the water it contains to produce more steam or condense steam in the bubble over the water. Water is circulated through the primary coolant system by the reactor coolant pumps. These pumps circulate the primary coolant water through the steam generators to produce steam in the secondary coolant system. The water from the secondary coolant loop is separated from water in the primary coolant loop by pipe walls inside the pressurizer so that any radioactivity which might leak from the fuel rods into the primary loop will not migrate from the containment building through the secondary coolant loop. Secondary coolant water is circulated through the turbine, the condenser, and back to the pressurizer by the main feedwater pump.

The plant also contains an emergency core cooling system (ECCS) to supply cooling water to the core in the event of a loss of coolant accident (LOCA). If the coolant is lost through a small break, the high pressure injection (HPI) pumps deliver water to the core from the borated water storage tank. If the break is large, the low pressure injection (LPI) pumps deliver water to the core, and the core flood tanks, situated above the core in pressurized tanks, deliver water quickly to give one of the other systems a chance to respond.

The Accident

The accident sequence has been detailed in three major reports published in the last year: a NRC report by the Office of Inspection and Enforcement (USNRC, 1979b); the Report of the President's Commission on the Accident at Three Mile Island (President's Commission, 1979) known as the Kemeny Commission report; and a report by the Nuclear Regulatory Commission Special Inquiry Group (1980) known as the Rogovin report. The three reports agree on important details of the accident sequence as reported here.

Shortly after 4:00 a.m. on Wednesday, March 28, 1979, TMI-2 experienced a feedwater pump failure while the reactor was operating at 97 percent of capacity. This cut off the flow of water to the steam generator which activated the plant's safety system. The automatic safety system shut down the steam turbine and the electric generator. Without the turbine operating to draw heat out of the secondary coolant system, the primary coolant loop began to heat up and expand. This caused pressure to build in the pressurizer to the point where the pilot-operated relief valve (PORV) on top of the pressurizer opened to release some steam and lower the pressure. The steam and water leaving the system through the PORV was not sufficient to prevent system pressure from rising. This caused the control rods to automatically drop down into the core to stop the chain reaction by the procedure known as a "scram." At this time, the exact cause of the initial feedwater pump failure is unknown but it is suspected that the failure was related to a maintenance procedure being performed at the time on a nearby resin filter in the feedwater system.

The reactor "scram" terminated the fission reaction in the core but some heat (about 6 percent of the heat released before the "scram") continued to be released to the cooling water due to the decay of radioactive materials left from the fission process. Three emergency feedwater pumps automatically came on to remove the decay heat from the core. Pressure in the system was being reduced to normal levels by the open PORV. Up to this point, the reactor system had responded normally and automatically to an abnormal but not particularly unusual turbine outage. Now, system problems began to assert themselves in such a way that the accident got out of control.

Thirteen seconds into the accident, the PORV should have automatically closed when system pressure dropped to 2,205 psi. Instead, the valve stuck in the open position draining coolant from the system. A LOCA was in progress. Control room operation did not know the valve was stuck open because the control panel had been designed to show the signal sent to the valve rather than the actual position of the valve. It was not until nearly 2-1/2 hours later that the problem was corrected by closing the block valve. The problem might have been corrected much earlier if the operators had not ignored the numerous instrument readings which indicated a stuck-open PORV, if they had not ignored the past failure history of this type of valve, or if they had been aware of the similar series of events which occured earlier at the Davis Besse plant in Ohio.

Fourteen seconds into the accident, it was noticed that the emergency feedwater pumps had been automatically activated but it was not noticed that the valves on the lines leading to the steam generator were closed. No cooling water was reaching the steam generators to remove the decay heat from the primary coolant loop. The control panel has two lights to show whether the valves are opened or closed. One light was covered by a yellow maintenance tag and the second may have been obscured by an operator leaning over the control panel. In any case, the problem was not detected and corrected until about eight minutes into the accident. The NRC Office of Inspection and Enforcement (USNRC, 1979b) has investigated nine separate possible causes for the closed valves but was unable to reach a definite conclusion as to which was the correct cause. This lack of emergency feedwater did not itself significantly affect the outcome of the accident except possibly through added confusion and distraction of the operators.

The water level in the pressurizer began to rise at forty-eight seconds into the accident. This was because the operators had turned on a pump which was supplying more water than could leak out through the PORV. Almost a minute later, the steam generators boiled dry because their feedwater supply had not been unblocked yet. This caused the primary coolant water to heat up, expand and send the pressurizer level up further. Two minutes into the accident, the emergency core cooling system's high pressure injection (HPI) pumps automatically switched on in response to a rapid loss of pressure. Continued water level rise in the pressurizer led the operators to believe the system had plenty of water in it even though the system pressure continued to fall and temperatures became constant. These facts should have alerted the operators that a LOCA was in progress. Unfortunately, the operators had been trained to never allow the pressurizer to go "solid" (fill with water) because they would then lose the ability to control system pressure. In order to avoid "going solid", one HPI pump was switched off after 2-1/2 minutes of operation and the other was throttled back to less than half its normal flow.

Steam bubbles began to form in the reactor coolant system when the saturation point was reached 5-1/2 minutes into the accident. Steam pockets began to form in high points in the primary coolant system, forcing coolant water into the pressurizer, out through the stuck-open PORV, and into the reactor coolant drain tank. Not realizing that coolant water was flashing into steam in the reactor and water was exiting through the PORV, the operators began draining water from the reactor's cooling system through the let-down piping in order to reduce the water level in the pressurizer. The operators also did not realize that these actions would lead to an uncovered core.

Shortly after 4 a.m., an alarm indicated water in the containment building's sump. The water exiting through the PORV to the drain tank had filled it to the point of bursting its rupture disk and spilling the overflow onto the containment building floor. As much as 8,000 gallons of slightly radioactive water may have been pumped automatically into a storage tank in the auxiliary building before the sump pumps were stopped.

TMI-2's four reactor coolant pumps began vibrating shortly after 5 a.m. The vibrations were due to the pumping of a mixture of steam and water. Two of the pumps were shut down at 5:14 a.m. and the remaining two were stopped 27 minutes later. The operators were following their training by turning off the pumps. The operators still believed the system was nearly full of water and hoped that natural circulation would cool the core. However, the large amount of steam in the system caused voids which prevented natural circulation.

It was at about this time that serious core damage began. By about 6:00 a.m., there was evidence that at least a few of the fuel rod claddings had burst from high internal gas pressure. Some radioactivity was thereby allowed to escape to the cooling water. Some of these radioactive gases reached the containment building through the PORV, as indicated by radiation alarms in the containment building. The fuel bundles in the core were more than half uncovered since only small amounts of water were being added and large amounts were leaving through the open PORV. The core became heated to the point where hydrogen was produced by the reaction of steam with the zirconium alloy fuel rod cladding. Some hydrogen escaped to the containment building where it exploded later in the day, and some formed a gas bubble in the reactor.

At 6:22 a.m., the pressurizer block valve was closed, stopping the flow of coolant water through the stuck-open PORV. It is not clear exactly who made the decision or for what reasons, but it was the first major correct move by the operators that day. However, they still did not realize that a LOCA had been in progress for over two hours up to the time the block valve was closed.

Between 6:00 and 6:30 a.m., radiation readings in the containment and auxiliary buildings markedly increased. Readings as high as one rem per hour were detected in the auxiliary building and a cooling water sample showed radioactivity levels about 350 times greater than normal. Shortly before 7:00 a.m., a site emergency was declared when it was realized that there had been fuel failure. A site emergency means that the immediate environment is threatened by a possible uncontrolled release of radioactivity.

The site emergency was escalated to a general emergency at 7:24 a.m. after a monitor in the containment building gave a reading of 8 rem per hour. The monitor is shielded by lead to cut the radiation reaching it by a factor of 100. The operators took the reading to indicate an actual radiation concentration of 800 rem per hour in the containment building. The general emergency was declared because the potential for serious offsite radiological health and safety consequences existed. Radiation monitoring teams measured offsite radiation levels in the area of less than one millirem per hour.

About this same time, the high pressure injection pumps were turned on briefly. As a result, relatively cold water rushed in to the core. At about 8:00 a.m., the HPI pumps automatically came on again for a moment. At 8:26 a.m., the HPI pumps were again turned on. The available accounts

disagree as to actually when the core became covered with coolant water but it was sometime between 7:20 a.m. and 10:30 a.m.

At some point about this time in the accident sequence (probably about 7:45 a.m.), neutron monitors later indicated that a portion of the core probably slumped or crumbled into a jumbled mass near the middle of the core. A crustlike solid layer probably formed which may have blocked the flow of coolant water in the area. This may have resulted in higher temperature which allowed more steam to form and react with the zirconium cladding to form more hydrogen. As temperatures rose, more fuel rods probably failed. This caused more radioactive fission products to be released to the coolant water. From there, radioactivity escaped to the containment building through the block valve which was periodically opened in an attempt to relieve pressure as water was being forced into the system. After exiting the pressurizer through the block valve, the radioactivity escaped to the containment building through the rupture disk on the attached drain tank. Radioactive coolant water also entered the auxiliary building through the let-down system.

The first of many major communication problems became evident when the Metropolitan Edison Company could not contact the NRC to notify them of the emergency before NRC offices opened at 7:45 a.m. Although too numerous to document here, communication problems were a conspicuous feature of almost all interactions in the days that followed. Decision makers at both the state and Federal levels were making important decisions based on information that was sometimes incomplete and sometimes incorrect. The press issued confused, misleading, and often incorrect reports. The press is not entirely to blame for this since there were too many official sources issuing conflicting information on which the press based its reports. The press was not, however, adequately prepared to deal with the technical content of the issues involved.

Shortly after 11:30 a.m., the operators attempted to depressurize the reactor system for reasons that are still not clear. This was attempted by opening the pressurizer block valve and cutting back on high pressure injection. The attempt was terminated after about 2-1/2 hours and resulted in the loss of more radioactive coolant to the containment and to another uncovering of the core. At 1:50 p.m., a "thud" was heard in the control room. It was accompanied by a 28 psi pressure spike in the containment building. These events were dismissed at the time but later understood to have been the result of a rapid hydrogen burn or explosion inside the containment building.

At 7:50 p.m., the operators successfully returned the reactor to the forced-cooling mode by restarting one of the reactor coolant pumps that had vibrated badly earlier. This action returned the reactor to the relatively stable condition in which it would remain for several weeks as it gradually cooled down. The major phase of the accident had ended. However, small radiation releases continued, and the official and the public awareness of the severity of the situation escalated considerably.

The following morning (Thursday, March 29), radiation monitoring showed readings of 5 to 10 millirem per hour on-site and 1 to 3 millirem per hour at nearby locations offsite. At 2:10 p.m., a helicopter measured a brief burst of radiation at 3 rem per hour 15 feet above the vent stack of the TMI-2 auxiliary building. These uncontrolled releases are thought to have originated from leaks in the let-down and make-up plumbing in the auxiliary building. Also that afternoon, 40,000 gallons of slightly radioactive (well within NRC limits) water was released to the Susquehanna River before the release was terminated by the NRC. The release resumed after midnight because the tanks holding the water were close to overflowing.

Controlled releases of radioactivity on Friday, March 30 were to cause further concern. Handling large quantities of radioactive materials without significant release to the environment while at the same time attempting to preserve emergency response capability poses logistical problems. Just such a problem was encountered on this morning. Radioactive water from the let-down system was flowing into the the make-up tank in the auxiliary building. Gases dissolved in that water were liberated because of the lower pressure in the tank. These gases are normally transferred to the waste gas decay tank for storage. Pressure from the gas in the make-up tank was so high that water which should enter the tank could not. At 7:10 a.m., the transfer of gas from the make-up tank to the waste gas decay tank was begun to relieve pressure in the former. It was known at the time that the vent heater between the two tanks leaked. The transfer was initiated anyway because the uncontrolled releases that could have resulted from not making the transfer were seen as being more serious. The decision was made to vent the make-up tank until it reached atmospheric pressure. A portion of the radioactive gas escaped through the leaking vent heater, into the auxiliary building, and out the stack to the environment. Radioactivity readings 130 feet above the stack reached 1 rem per hour at 7:56 a.m. and 1.2 rem per hour at 8:01 a.m. The maneuver was successful from the standpoint of plant operation but was to cause a major evacuation scare that brought the population close to panic.

NRC officials misinterpreted the 1.2 rem per hour reading as an off-site ground-level concentration rather than a reading above the stack. After hearing many conflicting recommendations, Governor Thornburgh advised that all persons within 10 miles of the plant stay inside. But word that the NRC had recommended evacuation reached the public and created near panic in the area. Shortly after 12:30 p.m., Thornburgh publicly recommended that pregnant women and preschool children evacuate a 5-mile radius from the plant and that schools in the area should close.

The next groundless public scare came on Saturday afternoon when NRC chairman Hendrie made public the notion of a hydrogen explosion in the reactor vessel. There is no question that a large amount of hydrogen was present in the reactor vessel but hydrogen will not explode unless there is sufficient oxygen present to create an explosive mixture. It was feared that this could happen by the process of radiolysis in which water molecules are broken apart by radiation to liberate hydrogen and oxygen. The fact that the oxygen would recombine with hydrogen to form another

water molecule before an explosive mixture could accumulate was overlooked in the calculations on which the explosion fears were based. By Sunday afternoon, NRC knew that their calculations were in error and that no threat of an explosion existed. NRC did not announce until Monday that their calculations were "too conservative." By midafternoon on Sunday, it became evident that the large hydrogen bubble had dissipated into smaller bubbles throughout the system and was no longer cause for concern. NRC did not announce that the bubble had been eliminated until two days later.

It was not until nearly a month later, on April 27, that cold shutdown was finally reached.

The Cleanup

Just over one year after the TMI-2 acccident began, Wilson (1980) of the General Public Utilities Service Corporation (parent of Metropolitan Edison Company) summarized current plant conditions and the plans for cleanup. The conditions and plans reported below were as of March 1, 1980.

Current conditions are:

- Reactor coolant is at 150 degrees Fahrenheit, 300 psi and is circulating on an 18 hour period by natural convection. Pumps were turned off because two phase (water and steam) flow caused excessive pump vibrations;
- There are now no unintended radioactive releases;
- The auxiliary building has been partially decontaminated;
- There are over one million gallons of highly comtaminated water on site, of which about 640,000 gallons are the most highly active cooling water now circulating;
- Water is processed on site by ion exchange systems. An evaporation process is being installed to clean the water which will be used to scrub the containment; and
- The containment building has been penetrated with radiation monitors, water and gas samplers and a TV camera. Krypton-85 is the main radioactive gas of concern. There are seven feet of radioactive water on the containment building floor.

The planned cleanup sequence is:

- Enter the containment building to recover samples
- Vent gas
- Remove and treat water
- Use high pressure hoses to wash all surfaces

- Scrub all surfaces by hand from top down
- Remove reactor vessel head which may have "things" stuck to it
- Examine core
- Remove fuel, place it in canisters shaped like fuel rods and store on or off the site
- Replace or refurbish core
- Refurbish the containment building.

Also according to Wilson (1980), the cleanup is expected to take 42 months assuming no regulatory delay and the availability of money. The reactor could be operational in 1984. The cleanup will involve the exposure of 12,000 workers to a total of 10,000 to 40,000 person-rem. Workers have been drawn to date from volunteers in the GPU system. To date, on the order of 20 workers have been exposed to radiation beyond the limits set by NRC. The wastes will include 10-15 thousand barrels of small solid waste, 1,000 cubic feet of waste machinery and 3-5 million gallons of water. The estimated $400 million cleanup cost does not include capital costs, replacement power costs or the effects of inflation.

A more recent report (Wall Street Journal, 1980) claims that the cleanup will take six years instead of four and that the new cost estimate is expected to "significantly exceed" the previous estimate of $400 million. GPU blames most of the delay and added cost on federal regulators who are applying stricter standards for the TMI facility than for normally operating facilities. However, the cleanup effort has been delayed by operational problems such as opening the containment building door. The door and other components may have been corroded by the atmosphere in the containment building.

On June 10, 1980, the NRC voted to allow the venting of radioactive krypton gas from the containment building (Chicago Sun Times, 1980). The NRC estimates that the containment building currently holds about 57,000 curies of krypton-85. A person standing outdoors at the site boundary for three-quarters of the 90 hour release period would receive an exposed skin dose of 10 millirem and a whole-body dose of 0.1 millirem (UNRC, 1980). This whole-body dose is approximately equivalent to 1 percent of the dose from a chest or dental X-ray examination. Residents of the area are nonetheless concerned about the releases.

RESPONSES TO TMI

Introduction

Responses to the Three Mile Island accident have come from all parties with an interest in nuclear power. For purposes here, responses from President Carter's Administration, the NRC, the industry and the public are introduced. The material that follows is not a complete treatment of the responses of these various groups, for that is given in the references cited, but rather an overview of the major findings, recommendations and responses of these sectors to the accident.

The Administration's Response

The Administration's reaction to the TMI accident was to appoint a Presidential Commission to study and make recommendations regarding the accident and then to respond to those recommendations. The President's Commission on the Accident at Three Mile Island was established on April 11, 1979 by Executive Order 12130 (Carter, 1979). The order said in part that "[t]he study and investigation shall include:

(a) a technical assessment of the events and their causes;

(b) an analysis of the role of the managing utility;

(c) an assessment of the emergency preparedness and response of the Nuclear Regulatory Commission and other Federal, state and local authorities;

(d) an evaluation of the Nuclear Regulatory Commission's licensing, inspection, operation and enforcement procedures as applied to this facility;

(e) an assessment of how the public's right to information concerning the events at Three Mile Island was served and of the steps which should be taken during similar emergencies to provide the public with accurate, comprehensible and timely information; and

(f) appropriate recommendations based upon the Commission's findings."

The 12-member Commission (known as the Kemeny Commission after the chairman) issued its report (President's Commission on the Accident at Three Mile Island, 1979) on October 30, 1979. The Commission's major conclusion, as stated in the report is:

> "To prevent nuclear accidents as serious as Three Mile Island, fundamental changes will be necessary in the organization, procedures, and practices -- and above all -- in the attitudes of the Nuclear Regulatory Commission and, to the extent that the institutions we investigated are typical, of the nuclear industry" (p. 27).

Some of the study's findings are:

The Accident

- The accident occurred as a result of a series of human, institutional and mechanical failures.
- The accident was initiated by equipment failures.
- Equipment failures contributed to the failure of operating personnel to recognize the actual condition of the plant.
- Operating personnel training was deficient.
- Operating personnel made some improper decisions, took some improper actions, and failed to take some correct actions, causing a minor incident to develop into a major accident.
- Some operating and emergency procedures were inadequate.
- NRC and Babcock and Wilcox disregarded earlier warnings that operators needed clear instructions for dealing with events like those during the TMI accident.
- The control room was not adequately designed for emergency management.
- The cost of the cleanup, replacement power and a portion of the waste disposal will be between $1 billion and $1.86 billion, if the plant can be refurbished. The total cost will be significantly higher if it cannot be refurbished.
- WASH-1400 (USNRC, 1975) probabilities indicate that an accident of this kind should have been expected by the time of TMI-2.

Emergency Planning

- Planning for off-site radiological emergencies lacks coordination and urgency at all levels of government.
- In a number of important cases, the utility and its suppliers failed to acquire enough information about safety problems, failed to analyze adequately the information they did have, or failed to act on that information. A similar problem existed in NRC.
- The GPU Service Corporation had final responsibility for design of the plant but did not have the staff or expertise in certain areas to carry out that responsibility. The Metropolitan Edison Company did not have sufficient knowledge, expertise or personnel to operate or maintain the plant adequately.

- Although the training program for TMI operating personnel met NRC standards, it was inadequate and contributed significantly to the seriousness of the accident.

Health Effects

- Between March 28 and April 27, 13 to 17 curies of iodine and 2.4 million to 13 million curies of noble gases were released to the environment.

- No detectible amounts of long-lived radioactive cesium or strontium escaped to the environment.

- The collective dose to the population living within 50 miles of TMI-2 between March 28 and April 15 is estimated to be 2,000 person-rem. This is somewhat less than one percent of the annual background level. Those within five miles of the plant received a dose that was about 10 percent or less of background.

- Present knowledge indicates that these doses will result in no detectable additonal cases of cancer, developmental abnormalities or genetic ill-health.

- The major health effect appears to have been on the mental health of people living in the area.

- Much larger quantities of radioactive materials were retained within the cooling system, the containment building and the auxiliary building.

- Cleanup and recovery presents additonal sources of possible radiation exposure.

- Even if a meltdown had occurred, there is a high probability that the containment building and the hard rock on which it is built would have prevented the escape of a large amount of radioactivity.

The Nuclear Regulatory Commission

- NRC is so preoccupied with the licensing of plants that it has not given primary consideration to overall safety issues.

- NRC issues operating licenses even though some safety problems that relate to a number of plants have not been resolved.

- In licensing a reactor, the full safety review does not occur until the operating license stage. The ultimate safety review may be influenced by economic consideration of the sunk costs that can lead to a reluctance to order major changes related to safety.

- Serious inadequacies in the NRC licensing process include: applicants are required to analyze only "single-failure" accidents and not the independent failure of two systems or components; there are no precise criteria for designation of "safety-related" components causing NRC to overlook important safety issues; there is no NRC office clearly responsible for overall systems engineering examinations; there is no NRC office responsible for human factors engineering; and there is no systematic review of operating plants with a view toward backfitting in response to new safety guidelines.

- The NRC commissioners have largely isolated themselves from the licensing process and the overall management of the NRC.

- NRC paid insufficient attention to small LOCAs in licensing reviews.

- NRC has no systematic method of evaluating operating experiences and looking for danger signals, although they do accumulate the information needed for such an analysis.

- Communication within NRC is deficient.

- Serious deficiencies in NRC's Office of Inspection and Enforcement include: heavy reliance on the utility's self-evaluation even when there are strong financial disincentives to evaluate and report safety problems; safety issues raised by inspectors are at times not seriously considered within the Office; and effective use has not been made of NRC's authority to assess fines for significant violations.

- NRC is unable to provide an acceptable level of safety for nuclear power plants with its present organization, staff and attitudes.

On the basis of these and other findings, the Kemeny Commission made numerous recommendations. The one which has received the most attention calls for the restructuring of the NRC as a new independent executive branch agency, headed by a single administrator from outside the present agency. The administrator would be appointed by the President, subject to approval by the Senate. It was recommended that the new agency should adopt an integrated approach to nuclear safety with expanded powers directed toward stricter regulations and closer supervision of the industry.

The establishment of an oversight committee on nuclear reactor safety is also recommended. The 15-member committee would avoid a narrow technical view by considering overall safety and policy issues. The role of the Advisory Committe on Reactor Safeguards (ACRS) should be strengthened. The ACRS currently provides the only review of reactor safety independent of NRC. However, the ACRS is funded at a relatively low level and must therefore rely on the NRC staff for support. The report also calls for emergency planning and remote siting as licensing conditions.

In the industrial sector, the report placed emphasis on the need for upgrading management and operating personnel to prevent and control accidents. Management should place more emphasis on the resolution of safety questions. The competence of operating personnel should be increased through higher pay scales and graduation from an agency-accredited training institution that stresses fundamentals of nuclear power plants, possible health effects of nuclear power and emergency response. Although the report notes many mechanical and design problems in its account of the accident, these were not emphasized in the recommendations.

President Carter's reaction to the Kemeny Commission report was given in a speech on December 7, 1979 and specified in writing in a White House Fact Sheet (Office of the White House Press Secretary, 1979). The President announced that he "agreed fully with the spirit and intent of the Kemeny Commission's recommendations" and would press forward with the recommendations within his power to implement. Carter does not, however, intend to reorganize the NRC along the lines suggested by the Kemeny report but will appoint a new NRC chairman from outside the agency and expand the chairman's executive authority. A five-member expert advisory committee will be established rather than the 15-member oversight committee proposed by the Kemeny Commission. The President agrees with the remainder of the recommendations and has taken action to see that they will be implemented.

The President has also added the following:

- NRC and other agencies should accelerate programs placing a resident Federal inspector at each reactor site. NRC should also investigate other means of supervising control room operations by placement of either observers or computer monitors in all control rooms.

- A supplemental appropriation of $8.9 million will be submitted to Congress so that the Federal Emergency Management Agency can assume responsibility for all off-site planning and response for nuclear emergencies.

- A supplemental appropriation bill of $49.2 million for NRC and $7 million for DOE will be submitted to speed the implementation of reforms based on lessons learned from TMI-2.

The Nuclear Regulatory Commission's Response

The NRC has responed to the accident at Three Mile Island through a series of reports from in-house groups and outside contractors. Prominent among the outside contractor reports is the one from the Nuclear Regulatory Commission Special Inquiry Group (1980) also known as the Rogovin report after the director of the study. The NRC contracted with the law firm of Rogovin, Stern and Huge to provide an independent review of the accident which would contribute to the full understanding of the accident from both a technical viewpoint and from the standpoint of the functioning of NRC's regulatory processes. Although the charge of this group was somewhat different from that of the President's Commission, the reports

and their conclusion were quite similar.

The Special Inquiry Group's general conclusion points out that "... the principal deficiencies in commercial reactor safety today are not hardware problems, they are management problems" (p. 89). Technical solutions are necessary but not sufficient to ensure safety. Some technical suggestions are given in the report. The summary goes on to state that "[i]n our opinion the [Nuclear Regulatory] Commission is incapable, in its present configuration, of managing a comprehensive national safety program for existing nuclear power plants and those scheduled to come online in the next few years adequate to ensure the public health and safety" (p. 89).

Among the recommendations of the Special Inquiry Group are the following:

- NRC should establish a program for the systematic evaluation of operating experience.
- NRC should improve its regulation of operating reactors.
- NRC should improve its inspection program.
- Operator training should be improved.
- An NRC-qualified engineer supervisor should be present on every shift.
- An industry-run offsite data center should be established.
- A national operating company or consortium should be chartered to upgrade site crew and management competence.
- NRC should be reorganized as a single administrator agency.
- Resources devoted to operating reactors should be consolidated.
- NRC should have a single office location which does not physically separate the Commission from the staff.
- An independent nuclear safety board should be established.
- The nonreactor safety responsibilities of NRC should be transferred to other agencies.
- Human factors engineering should be included in control room design.
- Instrument displays of plant status and important plant parameters should be upgraded or added.
- Nuclear plants should be sited away from populated areas.

- Adequate evacuation planning should be a license condition.
- NRC's emergency response capability should be enhanced.
- Licensing should be a one-stage process and should take place before construction begins.
- NRC should establish an Office of Public Counsel to intervene directly or to assist intervenors on safety issues and to fund and monitor independent technical peer review.
- The use of standardization should be increased.
- The basis for safety review of reactor design should be improved through increased use of quantitative risk assessment techniques.

The NRC also funded a study by The Essex Corporation (Malone et al., 1980) with the following objectives:

- "Establish if design of the interfaces between operators on the one hand, and equipment and information on the other, had an influence on the accident
- Determine if the control room at TMI-2 was designed according to human engineering methods, principles and standards
- Compare the design of TMI-2, from a human engineering standpoint, with the design of two other plants designed in the same time frame as TMI-2
- Determine if the design of TMI-2 is in compliance with NRC and industry standards and criteria
- Establish if design and use of procedures contributed to the accident
- Determine if manning levels and selection criteria contributed to the accident
- Establish if operator training contributed to the accident" (p. i).

The study found, among other things, that the control room was poorly designed, human engineering planning was virtually nonexistent, human error concerns were ignored by NRC and the nuclear industry, and procedures and training were deficient. The primary conclusion, supported by seven more specific conclusions, was that "... the human errors experienced during the TMI incident were not due to operator deficiencies but rather to inadequacies in equipment design, information presentation, emergency procedures and training" (Malone et al., 1980, p. V).

Among the numerous in-house reports issued by NRC since the TMI-2 accident is one that responds to the recommendations of the President's Commission. The report (USNRC, 1979d) indicates that NRC generally agrees with most of the recommendations of the President's Commission and plans to take, is taking or has already taken steps to implement those recommendations. There are, however, at least two major points on which there is disagreement. Four of the five NRC Commissioners believe that the objectives of the recommendation to reorganize NRC can be accomplished within the existing organizational structure by modification of internal practices and procedures and modest legislative action. The NRC is also not willing to relinquish its non-safety, antitrust and environmental protection responsibilities (USNRC, 1979d).

In the wake of TMI-2, NRC set up the Lessons Learned Task Force to identify and evaluate safety concerns stemming from the accident that require licensing actions. Two reports have been issued by the Task Force. The first dealt primarily with short-term technical recommendations in the areas of design, analysis and operations (USNRC, 1979a). The second addressed somewhat broader issues related to improvements in nuclear power plant design, regulation and operation (USNRC, 1979c). Although too numerous to present here, the recommendations in these two reports speak to most of the issues of concern within their scope.

The NRC Office of Inspection and Enforcement (IE) conducted an investigation to establish the facts concerning the events of the TMI-2 accident and to evaluate the performance of the Metropolitan Edison Company in connection with the accident with a view toward possible corrective or enforcement action. The IE report (USNRC, 1979b) identified dozens of items potentially in noncompliance with NRC regulations. The Metropolitan Edison Co. was later fined $155,000 for noncompliance in areas such as (1) reactor cooling system leaks in excess of allowable limits, (2) inoperable equipment, (3) failure to properly conduct emergency training drills and other procedures, and (4) improper radiation exposure records of workers.

A Special Review Group (SRG) within IE was also established to review the lessons learned from TMI-2. The SRG report (USNRC, 1979e) stated, in part, the following:

> "SRG finds that the IE inspection program was ineffective in certain preventive areas, and finds the need for: continued revision toward independent verification; increased emphasis on quality assurance programs, administrative control systems and vendor and design quality; increased emphasis on staff technical qualifications and formalization of qualification requirements; a more effective enforcement program; more attention to plant performance and its interpretations; and more effective channels of communications within IE and across the IE interface and other NRC staff components, particularly in the resolution of identified technical problems. In terms of interface and design considerations, the designation of safety-related systems must

be reconsidered and delineated so that the inspection program can be more effectively applied in the interest of safety" (pp. 3-4).

Based on these findings, numerous specific recommendations were put forward to improve the preventive and responsive aspects of IE's programs.

Following the accident, NRC suspended all licensing proceedings. Four pending operating licenses and five construction permit applications were affected. It was not until a year after the accident that permit reviews were resumed. During this time the NRC staff analyzed the many reports dealing with TMI-2 and established a number of corrective measures. All reactors with operating licenses were required to implement the short-term lessons learned from TMI which included such actions as the installation of new safety equipment and control-room operating procedures. Three nuclear plants were temporarily closed for failure to meet the January 31, 1980 deadline for installation of the new safety features. Particularly hard hit by these safety changes were the nine Babcock and Wilcox Co. reactors similar in design to TMI-2. Four of these plants were shut down and the reopening of five others undergoing routine maintenance was delayed until the safety changes could be made.

The Nuclear Industry's Response

Immediately following the accident, the nuclear industry formed the TMI Ad Hoc Nuclear Oversight Committee to coordinate the electric utility response to the accident. The Committee is a cooperative effort involving the Edison Electric Institute, the American Public Power Association, the National Rural Electric Cooperative Association and the Atomic Industrial Forum. They issued a paper (TMI Ad Hoc Nuclear Oversight Committee, 1980) which summarizes the industry response. Much of what follows was taken from this paper.

The U.S. nuclear power industry responded by revising procedures and training in nuclear power plants, by making equipment changes ordered by NRC, and by establishing organizations to correct the inadequacies indicated by the accident. Equipment changes have been expensive. Reed indicated in a recent paper (Reed, 1980) that Commonwealth Edison has spent about $5 million per nuclear unit to implement NRC's short-term lessons learned and that $50 million per unit may be required to implement the long-term lessons learned.

The organizations created by the industry to correct indicated inadequacies are the Nuclear Safety Analysis Center (NSAC), the Institute of Nuclear Power Operations (INPO) and Nuclear Electric Insurance Limited (NEIL). NSAC was designed to provide the utility industry with a medium for the exchange of technical information on questions of nuclear safety and in particular to analyze and disseminate information on non-normal events at nuclear reactors. NSAC's first major effort was the publication of a detailed analysis of the TMI accident. This report (Nuclear Safety Analysis Center, 1979) was published in July and was followed by a supplement in October. NSAC has also published a bibliography (NSAC, 1980) of

all TMI documents. NSAC is operated for the electric utility industry by the Electric Power Research Institute and has a staff of 50 technical experts drawn from the industry.

INPO was established to fill the vacuum in monitoring and reviewing nuclear operations and training. The immediate goal of INPO is to establish "benchmarks of excellence" in nuclear power plant management and operations. The Institute will also address the "... training of plant personnel, increased use of simulators, review and analysis of nuclear power operating experience, emergency preparedness and human factors in plant design" (TMI Ad Hoc Nuclear Oversight Committee, 1980, p. 14). INPO's headquarters are in Atlanta and it has a 1980 budget of $11 million, contributed by member utilities in proportion to the size of their nuclear programs.

In response to the high cost of replacement power placed on the General Public Utilities Corp. and its customers, the Nuclear Electric Insurance Limited was created. NEIL will provide a measure of protection against a utility's financial risk from a nuclear accident as opposed to its personal or property damage liability. NEIL is based on the mutual insurance concept and would cover a portion of the replacement power costs due to an extended reactor shutdown caused by an accident. Annual premiums would be about $1.7 million per reactor. The maximum loss that could be covered is $156 million over a two-year period.

The Public's Response

The initial response of the American public to Three Mile Island, particularly those in the immediate vicinity, was one of confusion and alarm. According to the reports issued by the Kemeny Commission (President's Commission on the Accident at Three Mile Island, 1979) and the Rogovin Special Inquiry Group (Nuclear Regulatory Commission Special Inquiry Group, 1980), this response resulted in large measure from the inaccurate information released by the Metropolitan Edison Company and the Nuclear Regulatory Commission. To quote the Kemeny report "[t]here was lack of communication at all levels. Many key recommendations were made by individuals who were not in possession of accurate information, and those who managed the accident were slow to realize the significance and implications of the events that had taken place" (p. 17).

Another factor contributing to the public confusion was the lack of effective coordination and collaboration between utility, state and federal authorities. This was particularly evident in the case of evacuation plans. For example, a mistaken interpretation of events on Friday March 30 resulted in a recommendation by some NRC officials that immediate evacuation be ordered by all residents ten miles downwind from the plant. In fact, later that day Governor Thornburgh did order an evacuation of all pregnant women and children under two years of age residing within a distance of 5 miles from TMI. Later that same weekend, again as result of a misinterpretation of the hydrogen bubble occurrence, there was widespread discussion of a possible general evacuation of the area.

The accident at Three Mile Island was given extensive coverage by the news media. In general, the newspaper, television and radio coverage did not clarify the confusion surrounding the event. This was primarily the fault of the representatives from the utility and the NRC who provided the information to the press. The tendency of some of the technical personnel associated with the utility and NRC to use technical language without sufficient explanation, coupled with the lack of experts with scientific and engineering background in the news media, further exacerbated the situation.

In light of these facts it is not surprising that the public in the vicinity of TMI, particularly those with preschool children, suffered severe mental stress which was short-lived. In fact, this was the only measurable public health consequence of Three Mile Island.

However, the health of the nuclear option was significantly affected by TMI as measured by national polls. Figure 7.2 shows the trend line of the public acceptability of nuclear power. Prior to the accident, the public accepted nuclear power by almost two to one (57% to 31%). Immediately following TMI (APRIL 1979) the number opposing nuclear power (43%) almost equalled those in favor (44%). In the summer and early fall of 1979, public acceptability increased and the opposition decreased. With the release of the Kemeny report the percentage rejecting the nuclear option reached an all-time high of 47 percent with 42 percent continuing to favor nuclear power. In the intervening months, nuclear power has found somewhat more favor with the American public. In January of 1980, some 50 percent of the American public favored nuclear with 38 percent opposed. This conclusion is also supported in a study conducted during the period December 1979 through March 1980 by Louis Harris and Associates (Harris, 1980) for Marsh and McLennan. The Harris study finds 77 percent of the public agreeing with the statement "Nuclear power involves inherent risks but it is too important to abandon altogether at this time", while 19 percent disagreed. At the same time, the public concludes "There should be a temporary ban on licensing new power plants" by a margin of 57 percent to 37 percent. Thus, it would appear that the effect of TMI is to cause the American public to reassess the nuclear option. They would prefer to retain it, but at the same time, they are seeking additional assurances on the safety of the option.

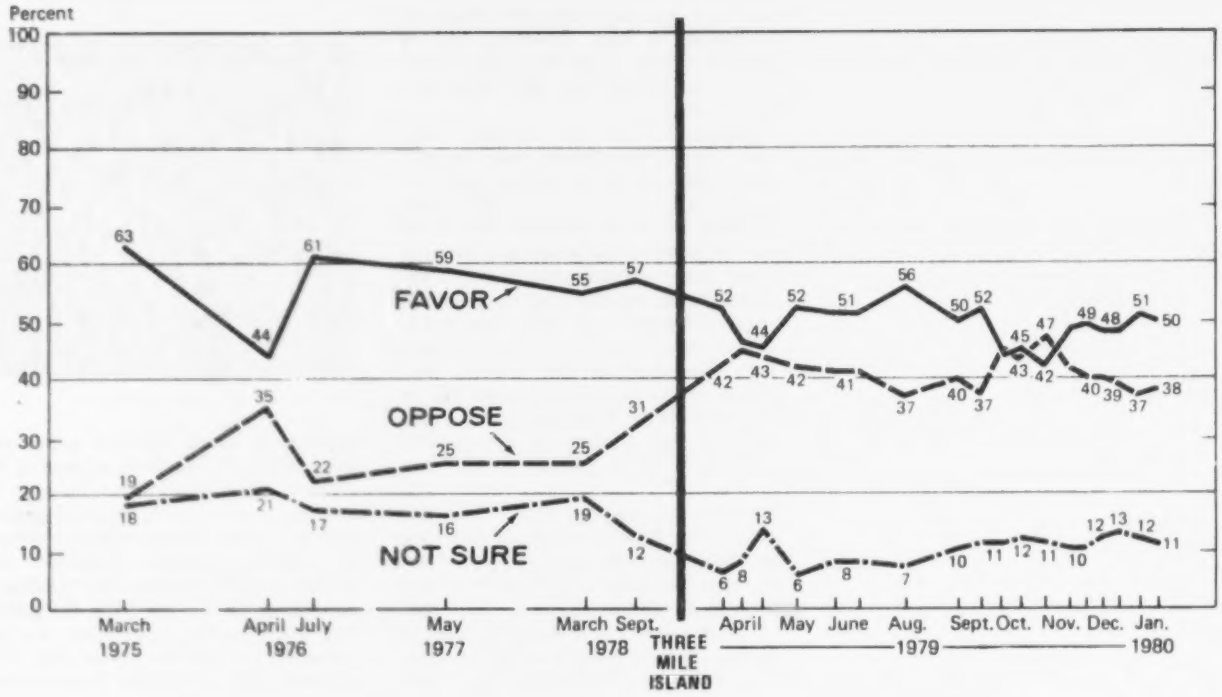


FIGURE 7.2. Harris Poll Trend Line on Building More Nuclear Power Plants

NOTE: Each poll in based on a national sample. Some were telephone but most were personal interview surveys. The question asked was, "In general, do you favor or oppose the building of more nuclear power plants in the United States?" Harris Poll data made available by the Edison Electric Institute.

SOURCE: Mitchell, 1980, p.6.

CHAPTER 8

SUMMARY

The presently known health impacts of the nuclear fule cycle operating under normal conditions are small. The literature surveyed indicates deaths to range from 0.1 to 0.85 per 1000 MWe reactor-year as a total for all functions within the present nuclear fuel cycle. When non-fatal health impacts are included, the comparable total rises to 3.7 to 14.1 health impacts per 1000 MWe reactor-year. Nearly 100 percent of these deaths and health impacts affect workers in the nuclear industry. Most studies conclude that uranium mining is the most dangerous fuel cycle stage with reactor-related impacts being the next most dangerous stage.

Comparable deaths from the coal fuel cycle range from 0.3 to 300 per 1000 MWe plant-year. When non-fatal health impacts are included, the figures are between 28 and 470 per 1000 MWe plant-year. Anywhere from 6 to 65 percent of these are estimated to be public health rather than occupational impacts. The large range in these figures is due to the uncertain health impact of coal-related air pollution. Air pollution from power generation may be responsible for as much as 96 percent of the deaths among the general public from the coal fuel cycle. Coal processing and coal transportation are responsible for the remaining public health impacts. Occupational deaths are, for the most part, attributable to the mining stage of the coal fuel cycle.

From an economic standpoint, either nuclear or coal electric generation may be more attractive, depending on the specific location of the plant. Location with respect to labor markets, coal fields, and the like are controlling factors. Capital costs are generally higher for nuclear plants than for coal plants. However, in several cases coal units with sulfur dioxide scrubbers are as expensive to build as nuclear plants. Operation and maintenance costs are generally lowest for coal-fired units without scrubbers, highest for coal-fired units with scrubbers, and intermediate between these two for nuclear plants. Nuclear fuel costs are significantly less than coal costs for a comparable amount of electricity production. The costs of nuclear facility decommissioning and nuclear waste disposal are not presently well specified. The general consensus at the present time is that these costs will be relatively minor.

There are other factors which must be considered in the evaluation of the relative risks and benefits of the nuclear and coal options. Both technologies are accompanied by risk aspects which are currently not well

known or possibly even totally unanticipated. The latter can, of course, not be discussed. The controversy over the health effects of low-level radiation remains unresolved, but current regulations are built around the conservative linear-dose response relation. Nuclear accident probabilities are also uncertain. Coal technology is also accompanied by presently ill-defined and potentially significant risks. These may include: sulfur dioxide emissions to the air which may come back to haunt us in the form of acid runoff if the buffering capacity of earth materials are exceeded or through other environmental health effects; carbon dioxide emissions to the air which may contribute to the warming of the earth through the greenhouse effect; unanticipated economic or environmental costs of cleaning stack gases; and unspecified economic or environmental costs of land or water supply disturbance through coal mining.

On the basis of the information presented in this report, there are several discernible arguments that can be use to reject nuclear power in situtations where it is economically competitive with coal. First, there are so few years of reactor experience that it is difficult to be confident in the accident probabilities and consequent risks calculated from this limited experience. To date, there are only about 500 reactor-years of operation which, when spread over the varying reactor types, gives extremely limited observational data for each reactor design. Although the occurrence of the Three Mile Island accident cannot be used to confirm or refute the accident probabilities based on previous experience, there is no absolute assurance that such accidents will not occur more frequently than current probability estimates indicate. The accident probabilities in the Reactor Safety Study (USNRC, 1975) are frequently used in reactor regulation. Even if these accident probabilities are low by a factor of 1000, the health impacts of the accidents treated would only be raised by somewhat less than 30 percent (Gaines, Berry, and Long, 1979). Nevertheless, this argument can be used to reject nuclear or any other potentially hazardous new technology unless the experience needed to inspire confidence in the risk probabilities has been accumulated prior to implementation. Such an approach necessarily places severe limits on, and in some instances would preclude, the growth of any potentially hazardous new technology such as nuclear power generation, unless greater uncertainty in risk factors is accepted. Another possible argument in favor of foreclosing the nuclear option is that the potential consequences of a nuclear catastrophe, however small the probability, may be unacceptable. Wilson and Jones (1974) present examples of situations in which the cumulative effect of a large number of small impacts is acceptable while the same total impact concentrated into a single event is unacceptable. Some may consider this to be the case with nuclear power.

Other arguments have been advanced by nuclear opponents in support of curtailing the use of nuclear power. These arguments, of course, have been countered by nuclear proponents. Opponents point out that no safe method of long-term waste disposal has been demonstrated. Proponents respond that, although technical problems have arisen in past programs, most experts agree that the waste disposal problem is basically one of political and institutional implementation rather than technical feasibility. Proponents further argue that long-term waste disposal is not

urgent at this time. Additionally, opponents are concerned over the lack of agreement among experts as to the health effects of low-level radiation. Nuclear advocates counter that only the low exposure end of the range is in question and it is agreed that the risk to society is low in any case. The possibility of nuclear sabotage or terrorism is also advanced as justification for abandoning nuclear power. Proponents argue in response that there are other more effective and more easily executed means of holding society hostage than attacking the commercial nuclear fuel cycle.

The future of nuclear power in this country is uncertain. The number of new nuclear reactor orders dropped off sharply six years ago. Since 1974, only seven orders have been placed. None have been ordered since 1978. Reduced demand for electricity is certainly a major cause for this downturn but regulatory constraints and uncertainties, cost escalation and public acceptability are probably also contributing factors. It is still a bit early to discern the long-term effect on the future of nuclear power resulting from the accident at Three Mile Island. It is likely that the short-term impact will be higher costs and a greater degree of safety.

No method of producing electricity is free of risks. Electric utility companies will probably continue to strive for a mix of generating sources to preserve reliable electric service in the event of supply disruptions. Coal strikes and oil embargoes are examples of supply disruptions already experienced. Currently, nuclear and coal technologies are the only practical alternatives for baseload electrical generation. Utility plans indicate that nuclear technologies will supply an increasing share of the electrical power generated in the ORBES region in the near future. Since the residents of the region are the recipients of the risks as well as the benefits of reliable electric service, they and their elected and appointed representatives should have a say in how that electricity is produced. Policies on risk acceptance are not completely amenable to quantitative analysis and are customarily achieved through the political process (Starr and Whipple, 1980, p. 1119). The jury is still out on nuclear power.

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APPENDIX A

REACTORS LOCATED OUTSIDE THE ORBES REGION AND INSIDE THE ORBES STATES

APPENDIX A

REACTORS LOCATED OUTSIDE ORBES REGION

State and Utility	Plant and Status	Location	MWe	Type/mfr	Operable
ILLINOIS					
Commonwealth Edison Co.	Braidwood 1 (C)	Braidwood	1,120	PWR/W	1981
Commonwealth Edison Co.	Braidwood 2 (C)	Braidwood	1,120	PWR/W	1982
Commonwealth Edison Co.	Byron 1 (C)	Byron	1,120	PWR/W	1981
Commonwealth Edison Co.	Byron 2 (C)	Byron	1,120	PWR/W	1982
Commonwealth Edison Co.	Zion 1	Zion	1,098	PWR/W	1973
Commonwealth Edison Co.	Zion 2	Zion	1,098	PWR/W	1974
Commonwealth Edison Co.	Quad Cities 1	Cordova	828	BWR/GE	1972
Commonwealth Edison Co.	Quad Cities 2	Cordova	828	BWR/GE	1972
Commonwealth Edison Co.	Carrol County 1 (P)	Carrol County	1,120	PWR/_a	1985
Commonwealth Edison Co.	Carrol County 2 (P)	Carrol County	1,120	_a	1986
INDIANA					
Northern, Indiana Public Service Co.	Bailly Nuclear 1 (C)	Dunes Acres	684	BWR/GE	1982
KENTUCKY					
NIL					

APPENDIX A

REACTORS LOCATED OUTSIDE ORBES REGION (Continued)

State and Utility	Plant and Status	Location	MWe	Type/Mfr	Operable
OHIO					
Cleveland Electric Illuminating Co.	Perry 1 (C)	North Perry	1,205	BWR/GE	1982
Cleveland Electric Illuminating Co.	Perry 2 (C)	North Perry	1,205	BWR/GE	1983
Ohio Edison Co.	Erie 1 (O)	Berlin Heights	1,267	PWR/B&W	1986
Ohio Edison Co.	Erie 2 (O)	Berlin Heights	1,267	PWR/B&W	1988
Toledo Edison Co.	Davis-Besse 1	Oak Harbor	906	PWR/B&W	1977
Toledo Edison Co.	Davis Besse 2 (LWA)	Oak Harbor	906	PWR/B&W	1985
Toledo Edison Co.	Davis Besse 3 (LWA)	Oak Harbor	906	PWR/B&W	1987
PENNSYLVANIA					
Metropolitan Edison Co	Three Mile Island 1	Londonderry Township	818	PWR/B&W	1974
Metropolitan Edison Co.	Three Mile Island 2	Londonderry Township	927	PWR/B&W	1978
Pennsylvania Power & Light Co.	Susquehanna 1 (C)	Berwick	1,050	BWR/GE	1980
Pennsylvania Power & Light Co.	Susquehanna 2 (C)	Berwick	1,050	BWR/GE	1982

APPENDIX A

REACTORS LOCATED OUTSIDE ORBES REGION (Continued)

State and Utility	Plant and Status	Location	MWe	Type/Mfr	Operable
PENNSYLVANIA					
Philadelphia Electric Co.	Limerick 1 (C)	Limerick Township	1,065	BWR/GE	1983
Philadelphia Electric Co.	Limerick 2 (C)	Limerick Township	1,065	BWR/GE	1985
Public Service Electric and Gas Co.	Peach Bottom 2	Peach Bottom Township	1,051	BWR/GE	1974
Public Service Electric and Gas Co.	Peach Bottom 3	Peach Bottom Township	1,035	BWR/GE	1974
WEST VIRGINIA					
NIL					

Note:
- C - Construction
- O - Order
- LWA - Limited Work Authorization
- P - Planned
- PWR - Pressurized Water Reactor
- BWR - Boiling Water Reactor
- GE - General Electric
- W - Westinghouse
- B&W - Bobcock and Wilcox
- a - Information not available

GLOSSARY

absorbed dose: The amount of energy imparted by ionizing particles to a unit mass of irradiated material at a place of interest. Also known as dose or dosage.

actinides: The group of elements of atomic number 89 through 103.

alpha (α) particle: A positively charged particle consisting of two protons and two neutrons, identical with the nucleus of the helium atom.

base load unit: An electrical generating unit designed to operate at constant output with little hourly or daily fluctuations.

beta (β) particle: An electron or positron emitted from a nucleus during beta decay.

byproduct material: Any radioactive material (except special nuclear material) yielded in or made radioactive by exposure to the radiation incident to the process of producing or utilizing special nuclear material.

capacity factor: The ratio of energy actually produced to that which would have been produced in the same period (usually a year) had the unit operated continuously at rated capacity.

chain reaction: A succession of generation after generation of acts of nuclear divisions such that the neutrons set free in the nuclear disruptions of the nth generation split the fissile nuclei of the (n+1)st generation.

core: the active portion of a nuclear reactor, containing the fissionable material.

curie (ci): A measure of the radioactivity level of a substance; one curie equals the disintegration of 3.7×10^{10} nuclei per second and is equal to the radioactivity of one gram of radium-226.

daughter: The immediate product of radioactive decay of an element, such as uranium. Also known as radioactive decay product or simply decay product.

decay product: See daughter.

disintegration: Any transformation of a nucleus, whether spontaneous or induced by irradiation, in which particles or photons are emitted.

dose: See absorbed dose.

fissile material: Atoms such as uranium-233, uranium-235, or plutonium-239 that fission upon the absorption of a low energy neutron.

fission: The splitting of an atomic nucleus into parts of comparable mass with an accompanying release of energy.

fissionable: A material capable of fission. Also know as fissile.

fission fragments: The nuclear species first produced when an atom such as uranium-238 or plutonium-239 undergoes fission.

fission product: Any radioactive or stable nuclide resulting from fission, including both primary fission fragments and their radioactive decay products.

gamma (γ) radiation: A high-energy photon emitted by a nucleus in a transition between two energy levels.

half-life: See radioactive half-life.

ionization: The process by which a neutral atom or molecule loses or gains electrons, thereby acquiring a net charge and becoming an ion.

ionizing radiation: Particles or photons that have sufficient energy to produce ionization in their passage through a substance.

irradiation: The exposure of a material to ionizing radiation.

isotope: One of two or more atoms with the same atomic number (i.e., the same chemical element) distinguished by variations in the number of neutrons in the nucleus. Isotopes usually have very nearly the same chemical properties but somewhat different physical properties.

light water reactor (LWR): A nuclear reactor that uses ordinary water as a coolant to transfer heat from the fissioning uranium to a steam turbine and employs slightly enriched uranium-235 fuel.

linear dose-response relation: The same proportional health effects are present at low levels of radiation as at high levels of radiation.

neutron: An elementary particle which lacks electric charge but which has approximately the same mass as the proton, and is a constituent of all nuclei having mass number greater than 1.

nuclear reactor: A device containing fissionable material in sufficient quantity and so arranged as to be capable of maintaining a controlled, self-sustaining nuclear fission chain reaction.

person-rem: A measure of human radiation exposure; it is the total dose in rem received by the individuals in a given population.

rad (radiation absorbed dose): The standard unit of absorbed dose, equal to energy absorption of 100 ergs per gram (0.01 joule per kilogram).

radioactive decay: The spontaneous transformation of a nuclide into one or more different nuclides, accompanied by either the emission of particles from the nucleus, nuclear capture or ejection of orbitial electrons, or fission.

radioactive half-life: The average time interval required for one-half of any quantity of identical radioactive atoms to undergo radioactive decay.

radiological: Pertaining to nuclear radiation and radioactivity.

rem (roentgen equivalent man): The unit of biological dose given by the product of the absorbed dose in rads and the relative biological efficiency of the radiation. A unit of ionizing radiation equal to the amount that produces the same damage to humans as 1 roentgen of high-voltage x-rays.

source material: Uranium or thorium, or any combination thereof, in any physical or chemical form, or ores which contain by weight one-twentieth of one percent (0.05%) or more of uranium, thorium or any combination thereof. Source material does not include special nuclear material.

special nuclear material: Plutonium, uranium-233, uranium enriched in the isotope 233 or in the isotope 235, and any other material which the U.S. Nuclear Regulatory Commission determines to be special nuclear material, but does not include source material; or any material artificially enriched by any of the foregoing but does not include source material.

transient: A pulse, damped oscillation, or other temporary phenomenon occurring in a system prior to reaching a steady-state condition.

transuranic radionuclides: Elements that have atomic numbers greater than 92; all are radioactive.

whole-body dose: A radiation dose may be delivered externally to the whole body or to specific organs or tissues through ingestion, inhalation, or other routes. A dose to a specific tissue may be translated into a whole-body dose equivalent.

x-rays: A penetrating electromagnetic radiation, usually generated by accelerating electrons to high velocity and suddenly stopping them by collision with a solid body, or by inner-shell transitions of atoms with atomic number greater than 10; their wavelength range from about 10^{-5} angstroms to 10^{3} angstroms.